Government of Central Kalimantan **Government of Indonesia** **Government of the Netherlands**

Master Plan for the Rehabilitation and Revitalisation of the Ex-Mega Rice Project Area in Central Kalimantan

THE SCIENCE OF TROPICAL PEATLANDS AND THE CENTRAL KALIMANTAN PEATLAND DEVELOPMENT AREA

Technical Review No. 1

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Euroconsult Mott MacDonald and Deltares | Delft Hydraulics
in association with
DHV, Wageningen UR, Witteveen+Bos, PT MLD and PT INDEC

Master Plan for the Rehabilitation and Rehabilitation of the Ex-Mega Rice Project Area in Central Kalimantan

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The Science of Tropical Peatlands and the Central Kalimantan Peatland Development Area

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1 Introduction

Peatlands are terrestrial wetland ecosystems in which the production of organic matter exceeds its decomposition and a net accumulation results (Joosten & Clarke, 2005). Several factors influence peat formation and preservation, including a positive climatic moisture balance (precipitation minus evaporation), high relative humidity, topographic and geological conditions that favour water retention, and low substrate pH, oxygen and nutrient availability (Moore & Bellamy, 1973). The majority of the world's peatlands occur in boreal and temperate zones where they have formed under high precipitation-low temperature climatic regimes. In the humid tropics, however, regional environmental and topographic conditions have enabled peat to form under a high precipitation-high temperature regime in Southeast Asia, mainland East Asia, the Caribbean and Central America, South America and southern Africa (Andriesse, 1988). It is estimated that more than 23 million hectares (62%) of the global area of tropical peatland occur in Southeast Asia (Table 1; Figure 1) where they occupy mostly low altitude, coastal and sub-coastal settings (from mean sea level to about 50 metres above mean sea level [amsl]) extending inland for distances of more than 200 km along river valleys and across watersheds (Rieley et al., 1996). They are most fully developed near the coasts of East Sumatra, Kalimantan, West Papua, Papua New Guinea, Brunei, Peninsular Malaysia, Sabah, Sarawak and Southeast Thailand (Figure 1) where rain forest vegetation grows on a thick mass of organic matter accumulated over thousands of years, to form deposits up to 20 m thick (Page et al., 2006). These lowland peatlands are almost exclusively ombrogenous (i.e. the peat surface only receives water from precipitation), whilst geogenous peatlands, that are fed additionally by water that has been in contact with the mineral bedrock and soils, are of more limited distribution along the edges of coastal lagoons, the banks and flood zones of rivers, and the margins of upland lakes (Rieley & Page, 2005). Undisturbed, lowland ombrogenous peatlands support peat swamp forest.

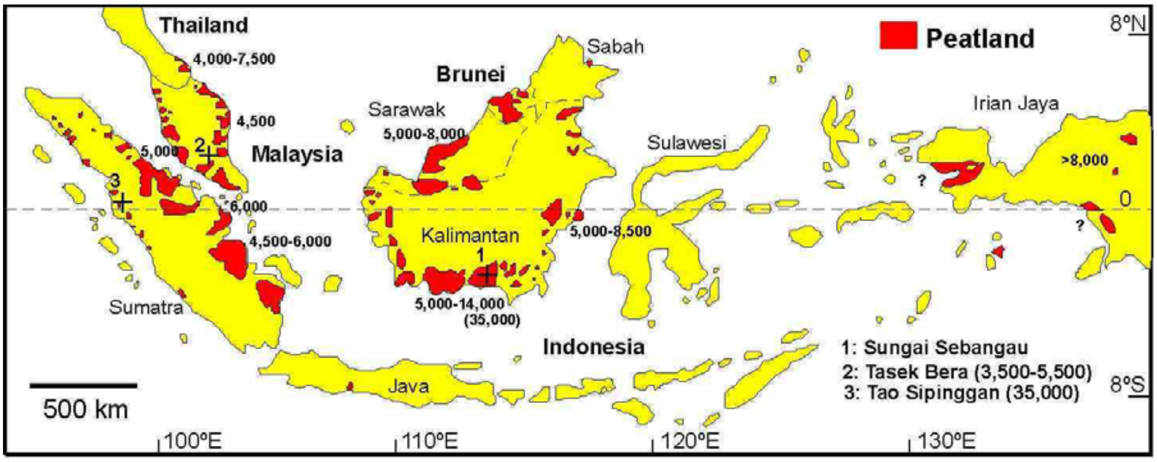


Figure 1: Peatland distribution in tropical SE-Asia. Ages of the initiation of peat accumulation in different locations are given (all ages are cal yrs BP) (from Page et al., 2004).

The total area of tropical peatland is around 40 million hectares, which is 10% of global peatland (Immirzi et al., 1992; Page & Banks, 2008; Page et al., 2008). The large range of values (26.7 – 56.5 million hectares) for the extent of the resource is indicative of the problems associated with making accurate assessments (Page & Banks, 2008), including (1) a lack of agreement on the definition of tropical peat soils, (2) the difficulty of accessing remote regions to carry out ground surveys, (3) application of different techniques used in surveying and mapping, especially for determining accurately boundaries between mineral and peat soils on remote sensed images, since both can support forest of similar structure, and (4) the rapid decrease in peatland area as a result of oxidation of peat soils, following forest removal, drainage, agricultural utilisation and fire, which renders survey data obsolete.

Tropical peatlands provide a range of valuable ecological functions and environmental services (Maltby et al., 1996; Page & Rieley, 1998). For example, they support a large diversity of plant and animal species, some of which are endemic or endangered (Page et al., 1997; Rieley & Page, 1997). Lowland tropical peatlands are important catchment and control systems that provide water for drinking and irrigation and, in coastal areas they are buffers between salt and freshwater hydrological systems (Boelter, 1964. Where the underlying mineral substratum is sulphidic, the peat layer acts as a protective wet sponge that keeps the mineral subsoil in an anaerobic condition, thus preventing the formation of highly toxic acid sulphate soils (Ritzema & Tuong, 1994). During the last 15 years, there has been increasing interest in peatlands globally because of their important role in the carbon cycle, which has raised the profile of tropical peatlands and stimulated scientific investigation of their carbon dynamics (Sorensen, 1993; Neuzil, 1997; Brady, 2002; Jauhiainen et al., 2002, 2004, 2005; Page et al., 2004; Wűst & Bustin, 2004). Tropical peat deposits store very large amounts of carbon and are also repositories of important geochemical and palaeoenvironmental information about past climates. In addition, lowland tropical peatlands have contributed to the way of life and economy of indigenous people for centuries through the provision of resources for food, shelter, medicine and cultural and spiritual well-being. They may continue to provide long-term support to the socio-economy of local communities but only if their characteristics are understood and they are managed in a sustainable manner (Rieley & Page, 2005).

In recent decades, tropical peatlands have come under increasing pressure from human-mediated disturbances, in particular, logging, drainage and conversion to agricultural land (Maltby et al., 1996). The associated changes in forest and land management practices have impaired the natural resource functions of the peatland ecosystem and, notably, increased greatly its susceptibility to fire (Page et al., 2002). In Southeast Asia during 1994, 1997 and 2002, there have been severe episodic droughts associated with the El Niño-Southern Oscillation (ENSO). In combination with forest degradation and land-use change activities, these dry conditions triggered widespread peatland fires leading to high levels of air pollution with serious consequences for human welfare and regional economies (Schweithelm, 1999). |On the other hand, drainage of tropical peatlands leads to oxidation and peat shrinkage, accompanied by subsidence. This increases the risk of flooding, particularly in low-lying coastal areas (Wösten et al., 2008).

2 Classification and Genesis of Peat in South-East Asia

In Southeast Asia, three general categories of lowland, ombrotrophic peatland have been proposed, based upon their location, mode of formation and the maximum age of the peat deposits: (1) coastal peatlands, (2) basin or valley peatlands and (3) high, interior or watershed peatlands (Anderson, 1983; Sieffermann, 1988; Rieley et al., 1996).

2.1 Coastal Peatlands

Coastal peatlands occur along the maritime fringe and in deltaic areas where they have developed over marine sediments of clay and silt at, or only slightly above, sea level (1-2 m amsl). They are situated inland of accreting mangrove and *Nipa* palm swamps, which they replace, and where the accumulation of organic deposits eventually excludes inundation by brackish waters. The abundance of toxic sulphides in waterlogged, brackish mangrove mud restricts bacterial activity enabling the initiation of peat formation under conditions of high rainfall and restricted drainage. The mangrove vegetation is replaced by peat-swamp forest and, as organic material continues to accumulate, the peat becomes increasingly ombrogenous, forming domed mounds.

2.2 Basin or Valley Peatlands

Basin or valley peatlands occur inland in sub-coastal locations along river valleys at slightly higher altitudes than coastal peatlands (5-15 m amsl), with which they may be contiguous. Peat formation in these appears to have been initiated as a result of rising ground water levels, linked to changes in sea level. Restriction of drainage led to permanent waterlogging and the establishment of freshwater herbaceous vegetation that, under high rainfall conditions, was followed by a transition to swamp forest and subsequent accumulation of ombrogenous peat. These basin peatlands are usually located along rivers in back swamp situations behind alluvial levees.

2.3 High Interior Peatlands

High, interior or watershed peatlands have only been described so far from Central Kalimantan where they cover low altitude watershed positions (10-30 m amsl) between major rivers. These peatlands are found about 100 km inland from the Java Sea and extend up to 200 km or more from the coast, occupying thousands of square kilometers with a thickness up to 13 metres. Peat formation commenced on top of the upper coarse sand layer of the ‘giant tropical podzol’ that extends across the middle of this province. The creation of an impervious ‘hard pan’ within the podzol, at a depth of several metres below the original mineral surface, gradually impeded vertical drainage and led to the waterlogging that was a prerequisite for peat initiation and accumulation.

The location and juxtaposition of these three major lowland tropical peat types within the Ex Mega Rice Project have not been studied in detail owing to a lack of field data and detailed examination of the peat. Their distribution is likely, however, to follow that of underlying mineral material, the largest area of which is underlain by recent, unconsolidated quaternary deposits consisting of layers of sand with clay lenses and rolled quartz gravels. This sedimentary material was levelled to a quaternary surface by one of several sea transgressions, some 50,000 years BP, before the latest great sea regression. It is referred to as the *'Palangka Raya Surface'* that has an east-west extension of almost 400 km and it the location of most of the basin peat and high peat deposits in Central Kalimantan (Sieffermann, 1988). In the coastal lowlands of Central Kalimantan peat covers the entire landscape at altitudes that are less than 60 m amsl and which appear to be virtually flat. This peat belt is crossed every 30 to 40 km by rivers separated by watersheds of about 20 m higher. High peat occupies the highest, watershed locations whilst the topographically lower river valley sides are occupied by basin peat. Peat transitional between these two major types can be found in intermediary positions while a small belt of shallower peat occurs between the basin peat and the river banks (Figures 3 and 4).

Studies of lowland tropical coastal peat deposits in Southeast Asia have demonstrated that they are the youngest peatlands in the region. Most of the peat started to accumulate around 4,000-5,500 YBP, following stabilisation of rising sea levels (Anderson & Muller, 1975; Neuzil, 1997). In comparison, investigations of sub-coastal and inland peatlands, particularly in Borneo, have revealed much earlier initiation dates, ranging from Late Pleistocene (~29,000 cal yrs BP) in the Danau Sentarum basin of West Kalimantan (Anshari et al., 2004) to ~26,000 cal yrs BP in the Sabangau catchment, Central Kalimantan (Sieffermann *et al*., 1988; Neuzil, 1997; Page et al., 2004), through to early Holocene (8,000-9,000 cal yrs BP) for other high and basin/valley peatlands (Staub & Esterle, 1994) (Figure 2).

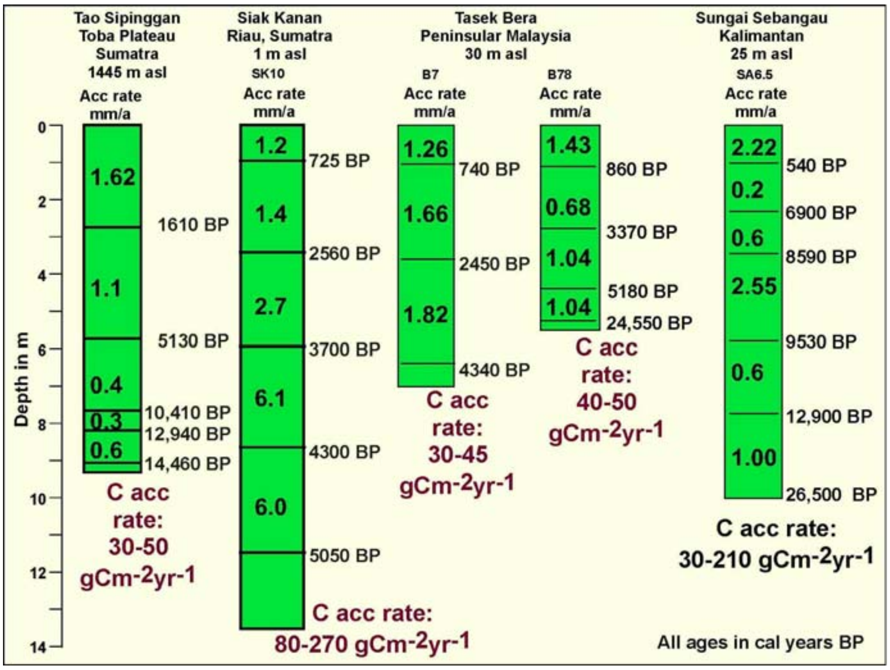


Figure 2: Selected peat cores from various sites in Sumatra, Peninsular Malaysia and Kalimantan showing age of peat accumulation, peat accumulation rates and C accumulation rates, the latter of which varied between 30-270 g C m^2 y^{-1}. (From Wűst, 2007; see Figure 1 for location of sites).

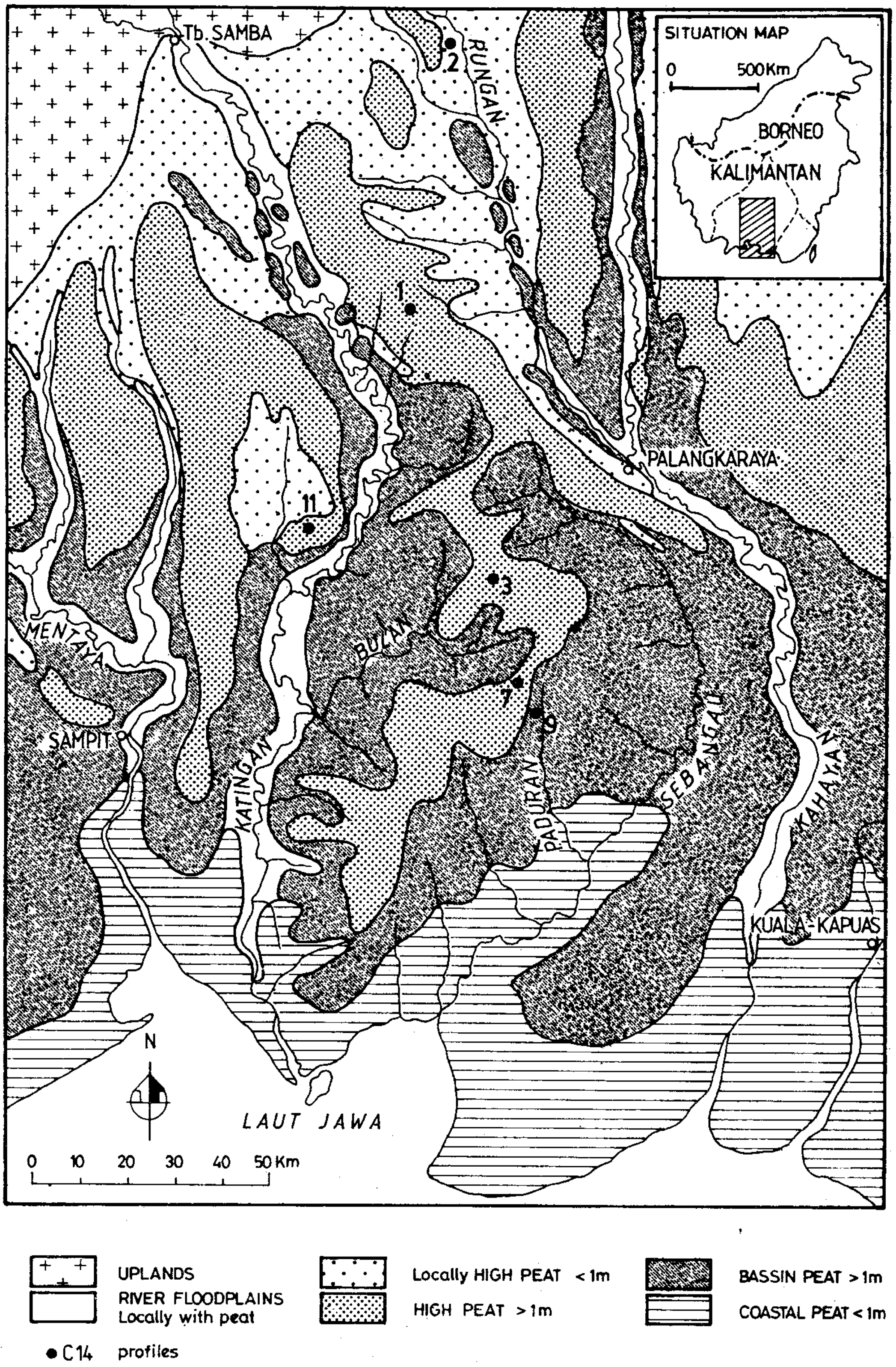
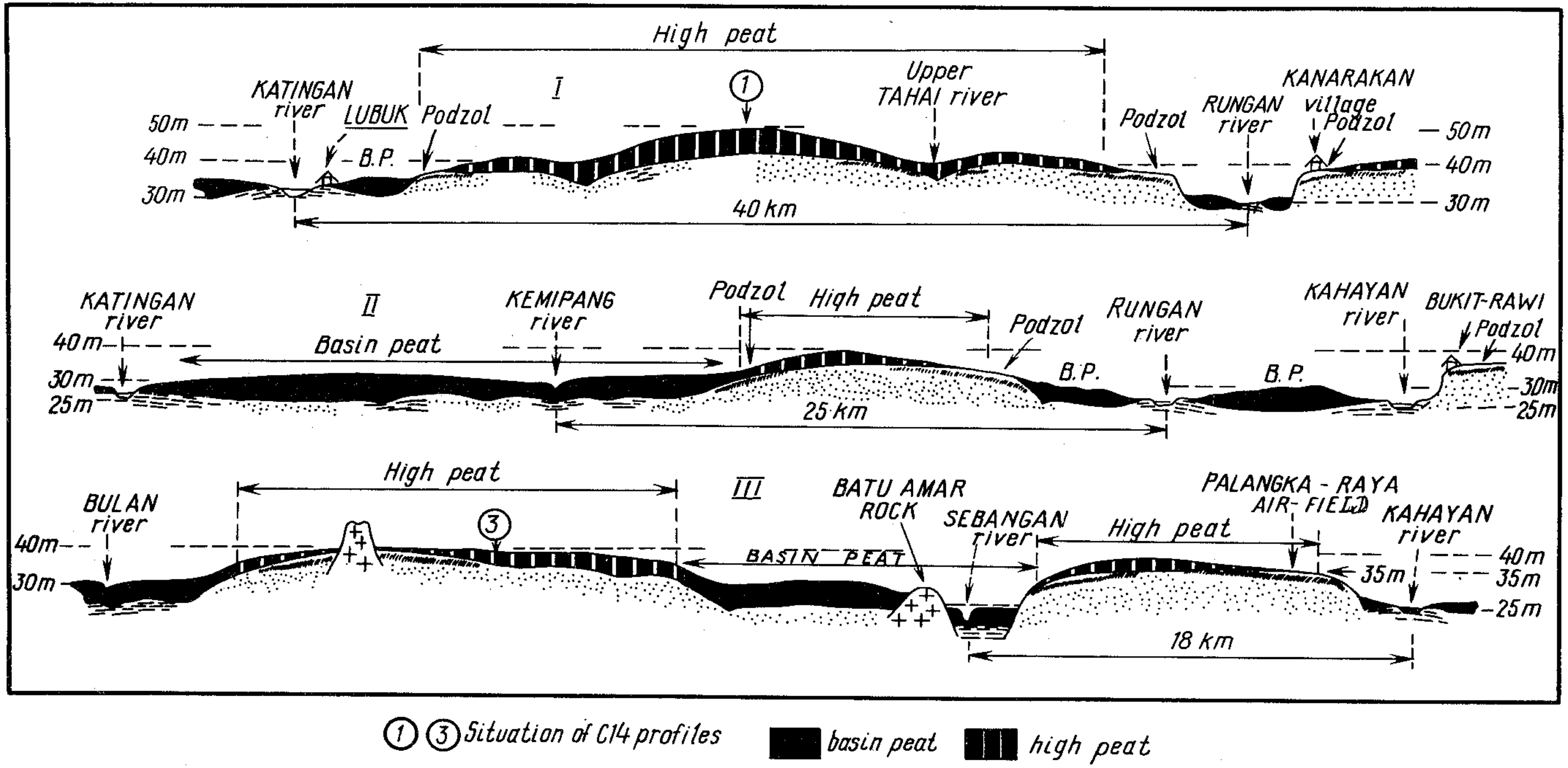


Figure 3: Distribution of peat types in Central Kalimantan (after Sieffermann, 1988)

Figure 4: Cross-section through peatland landscape in lowland Central Kalimantan (after Sieffermann, 1988)



3 Tropical Peat Soils

3.1 Classification of tropical peat soils

The classification of tropical peat soils has long been a controversial and confusing topic (Mutalib et al., 1992). Different approaches have led to poor correlation of information between countries and sometimes even within a single country. In Indonesia, swamps are differentiated into three broad zones, namely, brackish tidal land, freshwater tidal land and non-tidal land. The thickness categories used to classify tropical peat have also varied (Radjagukguk, 1997). In Indonesia the Centre for Soil and Agroclimate Research (CSAR) has classified lowland tropical peatlands into four depth classes: (1) shallow (50-100 cm); (2) moderate (100-200 cm), (3) deep (200-300 cm) and (4) very deep (>300 cm); the Land Resources Project used three categories, <50, 50-200 and >200 cm; while in the RePPRot Report a further three categories were used, <50, 50-300 and >300 cm (Widjaja-Adhi, 1997).

The United States Department of Agriculture Soil Taxonomy Classification has been adopted for the classification of peat soils in Indonesia (USDA, 1993), which are categorised as Histosols when the organic matter is >30% occurring in a 40 cm layer within the upper 80 cm of the soil profile[1]. Histosols are divided into suborders, primarily on the basis of their degree of decomposition.

3.2 Physical properties of peat soils

3.2.1 Peat humification

Once peat swamp forest is drained the peat starts to humify (i.e. the plant remains are converted into humus, the end product of the decay process) and the original raw peat, with its coarse root and tree remnants, decomposes slowly into humified peat, which has many small, uniform pores (Kurnain et al., 2002). The humification process has a strong influence on the hydraulic conductivity and moisture retention characteristics of the peat. The degree of peat humification can be expressed using the von Post Scale which ranges from H1 (least humified) to H10 (most humified) (von Post, 1924). For simplification purposes the 10 von Post classes are condensed and combined with information on fibre content, into 3 main peat types: (1) fibric, for undecomposed peat with a fibre content >66% and a low degree of humification, (2) hemic, for peat with a fibre content of 33-66% and a moderate degree of humification and sapric, for the most decomposed peat with a fibre content of <33% and a high degree of humification (Farnham & Finney, 1965; Esterle *et al.,* 1992) (Table 1).

Field observations indicate that most fibric peats are more than 200 cm deep, hemic peats 150 to 200 cm and sapric peats less than 100 cm; the critical limit of peat thickness for agriculture is 150 cm (Notohadiprawiro, 1986). The Agricultural Department of Sarawak, Malaysia, has set the critical limit at 100 cm, although some local farmers still obtain good yields on peat of more than 200 cm thick (Geurts & Andriesse, 1986). For lowland rice the

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[1] Peat usually requires an organic matter content of >65%

best thickness range is 30-60 cm (Leiwakabessy & Wahjudin, 1979).

Pore size distribution, determined by storage and delivery of nutrients and water improves at higher levels of decomposition. Compaction can improve pore size distribution although, for fibric and hemic peats, the improvement was not as good as in an uncompacted sapric peat. Compaction may be applied to peat to control nutrient leaching, enlarge the effective rooting volume and improve the soil moisture regime and may compensate for the effects of drainage. More advanced decomposition increases the nutrient status of peat.

3.2.2 Bulk density, particle density and total porosity

Bulk density is defined as the mass of soil (peat) per unit volume. Peat is light in weight when dry and the bulk density of the surface peat is only 0.15-0.30 g cm^{-3} compared to 1.25-1.45 g cm^{-3} for mineral soils (Brady, 1997b). Bulk density of surface peat in Central Kalimantan varies between 0.12 and 0.17 g cm^{-3} under pristine peat swamp forest while, in cultivated and fire damaged peatlands, it is higher, between 0.17 and 0.31 g cm^{-3}. After land reclamation peat substrates start to decompose and become compacted, leading to an increase in bulk density (Lambert & Staelens, 1993; Kurnain *et al*., 2001; Sajarwan *et al*., 2002).

Particle density of peat soils in Kalimantan varies between 1.23 and 1.76 g cm^{-3} (Lambert & Staelens, 1993; Kurnain *et al*., 2001; Sajarwan *et al*., 2002). For agricultural purposes, a single value of particle density is almost meaningless but, together with the bulk density, it reflects the total porosity and density of the peat. The total porosity of peat soils in Kalimantan, in general, varies between 80% and 90%. There is a lack of information, however, regarding the effect of peat drainage and reclamation on the total porosity, which tends to decrease with agricultural practices owing to peat compaction. This can lead to flooding in the rainy season and drought in the dry season.

Table 1: Simplified classification of peat based on humification

Fibre content	USDA classification	Corresponding Von Post class
Over 66%	Fibric	H1 to H3
33 – 66%	Hemic	H4 to H6
Less than 33 %	Sapric	H7 to H10

3.2.3 Swelling, shrinking and irreversible drying

Most peat soils shrink when dried but swell when re-wetted, unless water content falls below a threshold value beyond which irreversible drying and shrinkage occurs (Andriesse, 1988). Irreversible drying of peat in Central Kalimantan occurs at mean critical water contents ranging from 27.9 to 17.9%, 34.7 to 22.0%, and 5.5 to 3.5% for fibric, hemic and sapric peats, respectively (Kurnain et al., 2001). Shrinkage values can be expressed as specific volumes of peat (McLay *et al*., 1992). Specific volumes of peat from Kalampangan range between 2.7 and 6.5 cm^{3} g^{-1} decreasing significantly with cultivation and fire damage, especially in the top 0-30 cm layer (Kurnain *et al*., 2001).

3.2.4 Hydraulic conductivity

Hydraulic conductivity (ease by which peat pores permit water movement) in peat soils is controlled by several factors, including, total porosity, bulk density and degree of decomposition. Very few determinations of hydraulic conductivity have been carried out on tropical peat but those that are available range greatly from 0.2 to 52 cm h^{-1} (Sajarwan et al., 2002). Hydraulic conductivity varies owing to the differences in methods of determination employed and the difficulties in sampling peat soil without disturbing its field structure. Hydraulic conductivity of waterlogged peat 1-2 m below the surface of peat swamp forest in Central Kalimantan varies between 0.001 and 0.0001 cm sec^{-1} whereas, at the surface, it is so rapid that it is impossible to measure (Takahashi & Yonetani, 1997).

3.2.5 Moisture relationships

Information on the moisture relationships of peat is extremely important in reclamation, particularly for the design of efficient drainage layouts (Wösten et al., 1997). There are various methods of determining the moisture content of peat soils, each of which gives variable results in different kinds of conditions. The moisture relationships are often expressed as maximum moisture content (water holding capacity), moisture retention and available water. Similarly, moisture relationships are important in peatland restoration since different rehabilitation land uses require different hydrological regimes.

3.2.5.1 Maximum moisture content.

A study of pristine peat swamp forest in the upper Sungai Sabangau catchment, Central Kalimantan shows that maximum moisture contents of peat soils in the upper 15 cm peat layer vary between 700% and 1,080% on a weight basis (Kurnain et al., 2001). In contrast, in drained areas at Kalampangan, they range from 430% to 630%. When expressed on a volume basis the values are similar, ranging from 120 to 160%, because decrease in the maximum moisture contents after reclamation is followed by an increase in the bulk density.

3.2.5.2 Moisture retention.

Moisture retention by peat depends on the degree of decomposition, knowledge of which is important in the management of peat soils (Andriesse, 1988). Water appears to be increasingly held as the degree of decomposition increases. Fibric peat, for example, loses much of its retained water at low suctions.

For agricultural management the differences between the quantity of water retained at field capacity and the water retained at the permanent wilting point are defined as the amount of water available for plants. These values are measured quantitatively at pF 2.54 for the former and pF 4.2 for the latter. In practice, under field conditions, the quantity of water in peat soils appears to be much less than the quantity of water between these two pF values, perhaps because drought conditions are more severe than in temperate soils (Kurnain et al., 2001).

3.3 Chemical properties

3.3.1 Ash content

The ash content of peat and peat soils varies considerably from less than 5% to more than 65% (Rieley et al., 1996; Page et al., 2004). Higher values are attributed to increased mineral contents near to the underlying substratum. Ash contents of ombrotrophic peats are very low and do not change much with depth except at the surface and towards the base of the peat deposit. Under natural conditions ash contents of peat soils in Kalimantan are very low to low and vary between 0.2% and 2% (Lambert & Staelens, 1993; Kurnain *et al*., 2001; Sajarwan *et al*., 2001). When drained they range from 0.6-3% in Central Kalimantan and 1-9% in West Kalimantan (Page et al., 2004).

Ash contents of the peat in a 9.8 metre core in natural peat swamp forest in the upper catchment of Sg. Sabangau range from only 0.07% to 5.18% near to the underlying mineral substrate with an average of 0.22%. The surface peat has an ash content of 1.04%.

3.3.2 Soil pH and electrical conductivity

Under natural conditions the pH (H_2O suspension) of peat in Central Kalimantan is strongly acidic, ranging from 3.0 to 4.0, and tends to decrease with increasing depth in the peat. When drained, surface peat pH ranges greatly from 3.2 to 7.8, depending on utilization and management, in particular, addition of lime and fertilizers (Suryanto, 1994). At Kalampangan former transmigration village the pH of cultivated peat soil varies between 3.5 and 4.0 and is similar to that of pristine peat swamp forest adjacent to the cultivated area (Kurnain *et al*., 2001; Sajarwan *et al*., 2002). In South Kalimantan, however, the pH of cultivated peat soils ranges from 4.1 to 4.7 (Hadi et al., 2000).

Determination of electrical conductivity (EC) of peat soils is a very important requirement for agriculture as it provides an indirect estimate of the solubility of the ions required in plant nutrition. The EC of peat soils is usually much lower than that of mineral soils. At Kalampangan the EC of peat soils range from 40-100 $\mu S\ cm^{-1}$, reflecting the very low nutrient status in this area (Kurnain et al., 2001). In contrast, in the coastal peatlands of West Kalimantan, EC values of cultivated peat soils range from 140 to 320 $\mu S\ cm^{-1}$ (Suryanto, 1994), which is about three times higher than in Central Kalimantan.

3.3.3 Organic C, total N and C/N ratio

In contrast to mineral soils, the determination of a single value of organic carbon in peat soils is almost meaningless, particularly for agricultural development purposes, and should be combined with total nitrogen contents in order to calculate the C/N ratio. Organic C contents, total N contents, and C/N ratios of peat soils in the upper 100 cm profile at Kalampangan range from 49% to 57%, 1.0% to 2.2%, and 29 to 52, respectively (Kurnain et al., 2001). In the top 0-15 cm peat layer, organic C and total N contents tend to decrease with agricultural practices, whilst C/N ratios increase substantially.

3.3.4 Total phosphorus (P) and C/P ratios

Total P contents and C/P ratios of peat soils in the upper 100 cm profile at Kalampangan range from 0.4 to 0.7 $g\ kg^{-1}$ and 760 to 1,330, respectively (Kurnain et al., 2001). In contrast, in peat swamp forest of the upper Sg. Sabangau catchment, total P contents range from 0.3 to 0.9 $g\ kg^{-1}$ (Sajarwan et al., 2002). In the top 0-15 cm peat layer, total P contents decrease with agricultural use, whilst C/P ratios increase substantially. As peat becomes more decomposed under cultivation than in its natural state, mineralization of organic material releases N and P to the inorganic fraction of the soil and these are removed in drainage water. Total P and N contents in the lower layer of cultivated peat are higher than in the surface.

3.3.5 Cation exchange capacity (CEC) and base saturation

The sum total of the exchangeable cations that a peat soil can absorb (CEC), as commonly measured in peat soils at pH 7.0, is very high, usually more than 50 $cmol(+)\ kg^{-1}$, but is considerably less when it is determined at field soil pH because almost all of the surface charges are pH dependent (Lambert & Staelens, 1993; Lambert, 1995). Ion adsorption and exchange in peat are associated with hydrophilic colloids derived from humic substances, which have COOH and phenolic OH groups as complexing agents. The CEC of peat soils from South Kalimantan ranges from 70.6 to 132.8 cmol (+) kg^{-1} (Hadi et al., 2000).

4 The Tropical Peat Ecosystem

Lowland tropical peatlands provide a range of ecological functions and environmental services, including provision of habitat for biodiversity (plants and animals), water regulation and buffering against saltwater intrusion and underlying potential acid sulphate substrates, and carbon storage (Page & Rieley, 1998; Rieley & Page, 2005). In addition, they contribute to the way of life and economy of local people (Sjarkowi, 2002).

4.1 Vegetation

The vegetation of natural, lowland, tropical, peat swamp forest is dominated by tall forest trees many of which have buttress or stilt roots that provide improved stability on the waterlogged peat (Wyatt-Smith, 1959, 1964; Anderson, 1963, 1964, 1976, 1983; Page et al., 1999). Most have breathing roots (pneumatophores) that protrude above the peat surface, enabling respiratory gas exchange to occur under anaerobic, waterlogged conditions. The forest floor exhibits a well-marked microtopography, with small hummocks, up to 0.5 m in height, interspersed with hollows of similar depth. The hummocks consist of aggregations of tree roots and pneumatophores and are platforms for seed germination and seedling establishment. The hollows are only sparsely vegetated and form an interconnected network along which water flows from the interior of the peatland dome towards the rivers around the periphery.

The species composition and vegetation types of peat swamp forest are not uniform across Southeast Asia and there is local and regional variation (Rieley & Ahmad-Shah, 1996). Within one lowland tropical peatland catchment, there are usually between two and six different forest sub-types extending from shallow peat around the periphery onto the thick peat of the central peatland dome (Anderson, 1983; Brady, 1997; Shepherd *et al.,* 1997; Stoneman, 1997). This variation reflects a ‘catena’ of peat substrate of different peat thickness, height of the water table, duration of flooding and nutrient availability. In Central Kalimantan, peat swamp forest range from ‘mixed’ peat swamp with up to 240 tree species per hectare on shallow peat around the margins of the peat dome to a less diverse, low canopy, ‘pole’ forest, associated with the wettest, thickest peat, in which tree species number declines to 30–55 species per hectare (Page *et al.,* 1999) (Figure 5). Pollen analyses from peat cores in Central Kalimantan have shown that this continuum of forest types may represent an ecological succession over time (i.e. a gradual and orderly process of change in the peat swamp ecosystem as one community is progressively replaced by another until reaching a stable climax) (Anderson, 1964; Morley, 1981).

4.1.1 Forest types and structure of peat swamp forest in Central Kalimantan

The following peat swamp forest sub types were identified along a 25 km transect due west from Sg. Sabangau to the peatland dome (Page et al, 1999) (Figure 5).

Riverine forest

This forest type is intermediate between freshwater swamp forest on inundated mineral soils and peat swamp forest. It is located on shallow peat (up to 1.5 m thick) close to the river (up to 1 km from the edge) and is flooded by river water during the rainy season. The principal canopy tree species is *Shorea balangeran,* although *Campnosperma coriaceum* and *Combretocarpus rotundatus* are frequent. The sedge *Thorachostachyum bancanum* is characteristic in the ground vegetation. Most of this forest in the Sabangau catchment and elsewhere has been degraded severely by logging and burning and replaced by a secondary sedge swamp dominated by species of *Pandanus, Cyperus*, *Fimbristylis* and *Scleria*.

Transition forest (riverine - mixed swamp forest)

This occupies a very narrow zone (c. 1 - 1.5 km from the river) on peat of maximum 2 m thickness. It occurs at the limit of river flooding but is inundated by river water only following high rainfall and is influenced more by water outflow from the interior peat catchment. *Shorea balangeran* is the principal canopy tree.

Mixed swamp forest (Figures 5 and 6)

This extends up to 4 km from the margin of the peat dome into the interior. It is located beyond the limit of river flooding on peat that increases from 2 m to about 6 m in thickness. Trees grow on large hummocks formed by emergent roots, interspersed with hollows, which are filled with water during the rainy season. Many of the trees have stilt and/or buttress roots; pneumatophores are frequent. Typical trees of the middle and upper canopies include *Aglaia rubiginosa, Calophyllum hosei, C. lowii, C. sclerophyllum, Combretocarpus rotundatus, Cratoxylum glaucum, Dactylocladus stenostachys, Dipterocarpus coriaceus, Dyera costulata, Ganua mottleyana, Gonystylus bancanus, Mezzetia leptopoda, Neoscortechinia kingii, Palaquium cochlearifolium, P. leiocarpum, Shorea balangeran, S. teysmanniana* and *Xylopia fusca.*

Transition forest (mixed swamp - low pole forest) (Figures 7)

A slow gradation from mixed swamp to low pole forest can be observed between 4 and 6 km from the river. The upper and middle canopies are comprised of a similar range of species to those of the mixed swamp forest, although densities of *Calophyllum* spp., *Combretocarpus rotundatus* and *Palaquium cochlearifolium* are greater. Fewer trees exhibit buttressing or stilt roots; pneumatophores are abundant on the forest floor. Pandans (*Pandanus* and *Freycinetia* spp.) form an almost continuous ground cover.

Low pole forest (Figure 7)

This occurs at a distance of between 6 and 11 km from the river on peat that is from 7 to more than 10 m thick. The water table is permanently high and may be above the surface for several months during the wet season. The forest floor is very uneven with pronounced hummocks and hollows. The trees grow on island-like hummocks that are separated by deep, water filled hollows, in which water persists throughout the dry season. Tree pneumatophores are a constant feature and there is a dense mat of tree roots in the surface peat. Pandans form a dense, almost continuous ground cover and pitcher plants (*Nepenthes* spp.) are abundant. The principal canopy species are *Combretocarpus rotundatus, Calophyllum fragrans, C. hosei* with lesser amounts of *Campnosperma coriaceum* and *Dactylocladus stenostachys*.

Tall interior forest (Figure 8)

This forest occupies much of the most elevated part of this peatland dome where there is a relatively short and sharp transition from low pole forest. The peat water table inside this forest type is below the surface throughout the year. There are few obvious hummocks and hollows and most of the trees do not have pneumatophores. *Pandanus* spp. are absent except under gaps in the canopy. Canopy trees include *Agathis dammara, Calophyllum hosei, C. lowii, Cratoxylum glaucum, Dactylocladus stenostachys, Dipterocarpus coriaceus, Dyera costulata, Eugenia havelandii, Gonystylus bancanus, Gymnostoma sumatrana, Koompassia malaccensis, Mezzetia leptopoda, Palaquium cochlearifolium, P. leiocarpum, Shorea teysmanniana, S. platycarpa, Tristania grandifolia, Vatica mangachopai, Xanthophyllum* spp. and *Xylopia* spp. Several of these are of high commercial value

Very low canopy forest

This forest type is located on the highest point of the peat dome where it occupies a discrete area 13 km by 4 km surrounded by tall interior forest. This area has a permanently high water table and an abundance of very large pools, up to 1 m in depth, interspersed with tree covered islands. Pneumatophores are abundant and are most obvious protruding above the surface of the pools. Those of *Dactylocladus stenostachys* are particularly prominent, exceeding 1.5 m in height. Owing to the very open canopy, much light reaches the forest floor and there is a greater diversity and cover of mosses on the peat surface than in other forest types. There is, however, an absence of *Pandanus* spp. and the sedge *Thorachostachyum bancanum* is the most frequent vascular plant species of the forest floor. The commonest trees are *Calophyllum* spp., *Combretocarpus rotundatus, Cratoxylum* spp., *Dactylocladus stenostachys*, *Litsea* sp., *Ploiarium alternifolium* and *Tristania* spp.

Figure 5: Marginal mixed peat swamp forest in upper catchment of Sg. Sabangau, Central Kalimantan. LH is overview of canopy and RH is interior.

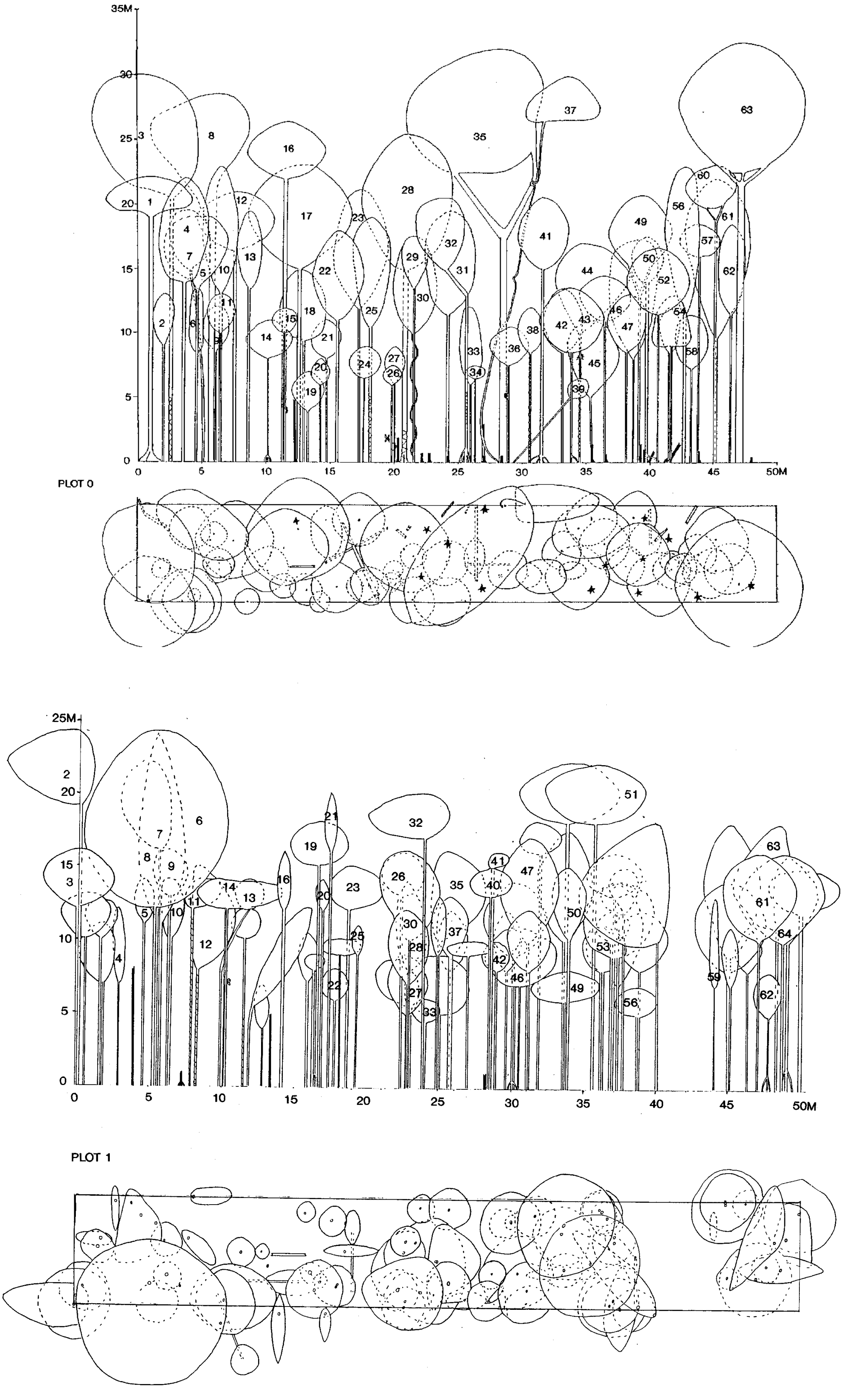
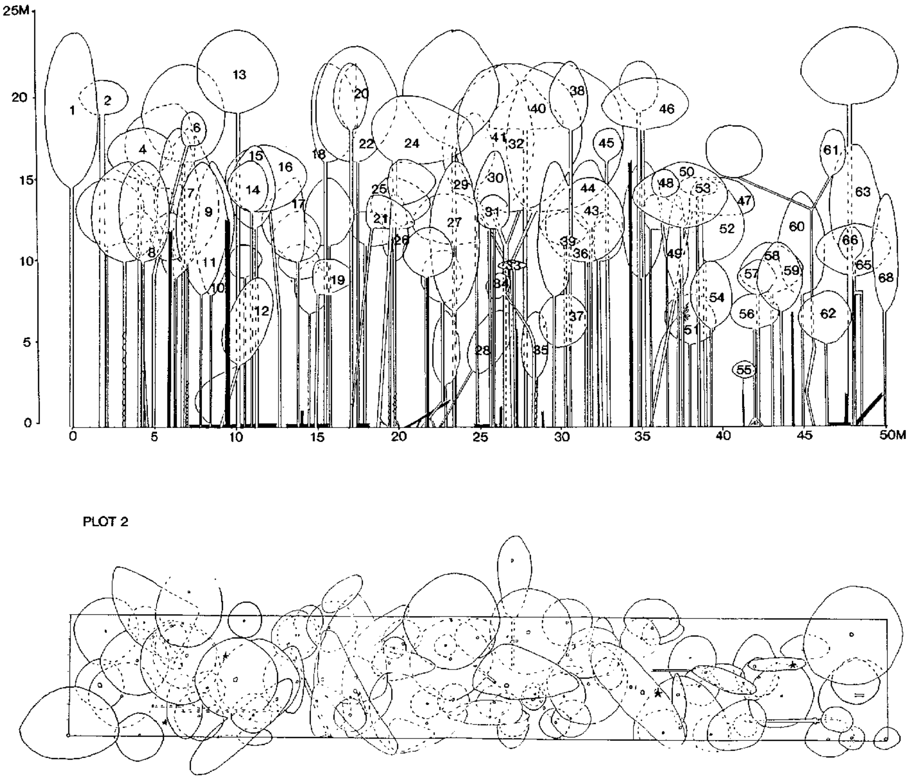
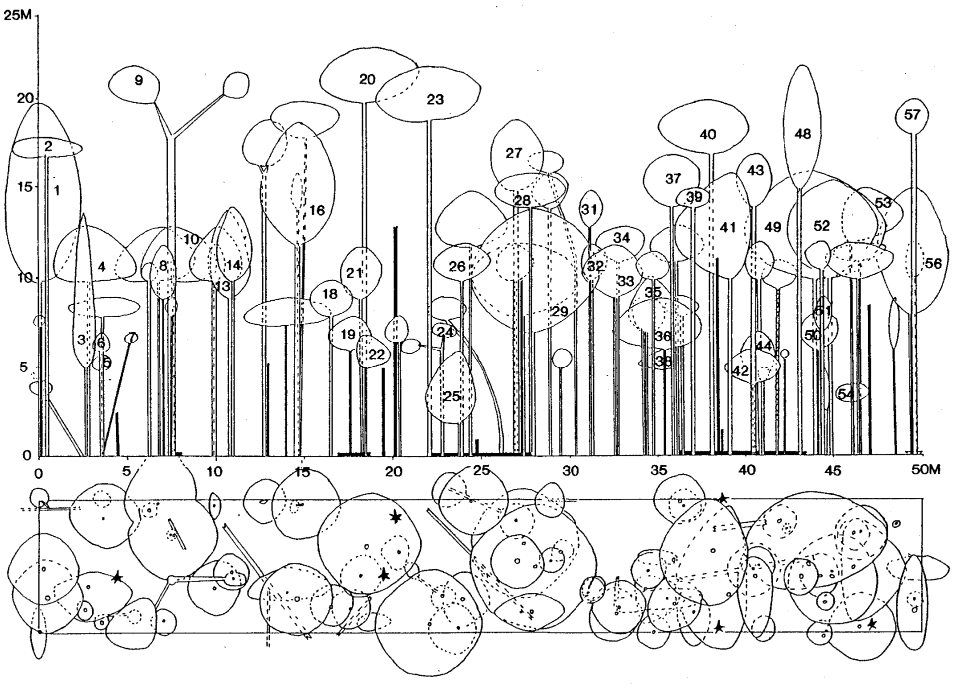


Figure 6: Profile through marginal mixed swamp forest 1-3 km from edge of peat swamp forest in upper Sg. Sabangau catchment, Central Kalimantan (Plot 0, top - mostly unlogged; Plot 1, bottom – heavily logged) (species codes are explained in Annex 1) (Rieley & Page, unpublished data)





PLOT 4

Figure 7: Profile through low pole forest 4-10 km from edge of peat swamp forest in upper Sg. Sabangau catchment, Central Kalimantan (Plot 2, top – unlogged transition from mixed swamp forest; Plot 4, bottom – unlogged centre of low pole forest) (species codes are explained in Annex 1) (Rieley & Page unpublished data)

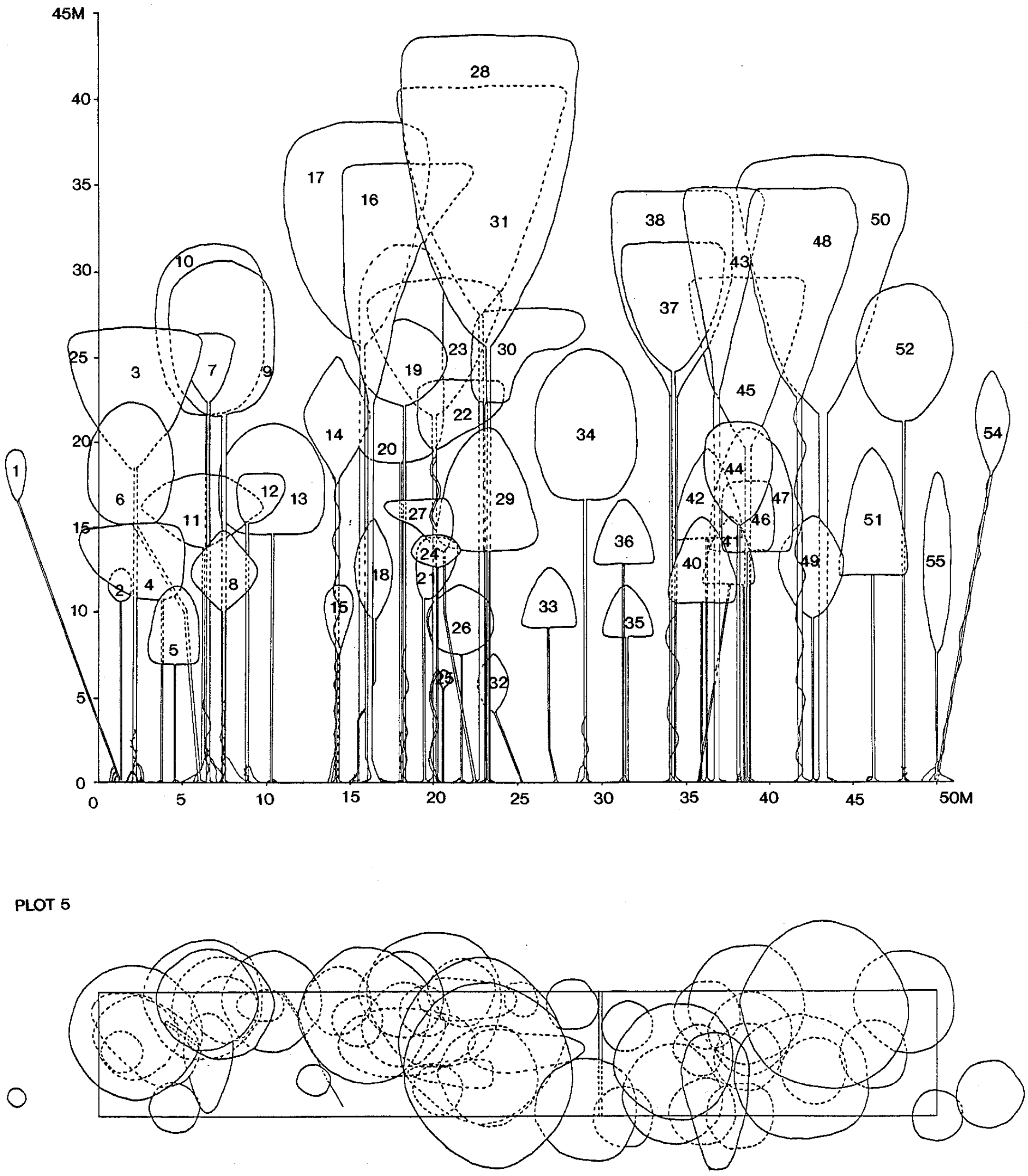


Figure 8: Profile through tall interior forest 15-25 km from edge of peat swamp forest in upper Sg. Sabangau catchment, Central Kalimantan (Plot 5 – partially logged tall forest with few emergents remaining) (species codes are explained in Annex 1) (Rieley & Page unpublished data)

4.2 Biodiversity

The plant and animal diversity of peat swamp forest is lower than in dipterocarp forest on mineral soils, but many species are endemic (restricted) to this ecosystem and thus make an important contribution to regional biodiversity (Shepherd et al., 1997). Many peatland species are specialists, which are not found or are declining in other habitats. The inaccessibility of peatland has also drawn in species that, although not confined to this habitat (e.g. orang utan), have become dependent upon the shelter and food it provides, owing to degradation and deforestation on the surrounding mineral soils. As more information on the biodiversity of tropical peat swamp forests accumulates it is clear that this ecosystem has been undervalued as a habitat for rare and threatened species (Laumonier, 1997).

In general, the taller peat swamp forest sub-types, which have the greatest tree species diversity and canopy stratification, support the greatest faunal diversity (Page et al., 1999). Low pole forest, with fewer strata, is less species diverse (Janzen, 1974) but is not without interest and several noteworthy species of mammals and birds have been recorded from it (Ng et al., 1994; Page et al., 1997).

4.2.1 Flora

Most of the tree families of lowland dipterocarp forests in Southeast Asia are found in lowland peat swamp forests (Polak, 1975; Whitmore, 1984) with members of the Anacardiaceae, Annonaceae, Burseraceae, Clusiaceae, Dipterocarpaceae, Euphorbiaceae, Lauraceae, Leguminosae, Myristicaceae, Myrtaceae and Rubiaceae being well-represented (Brünig, 1990; Flenley, 1985, 1998; Morley, 1981; Morley & Flenley, 1987; Ibrahim & Hall, 1992; Shepherd et al., 1997; Wyatt-Smith, 1959).

Characteristic and widespread tree species include *Baccaurea bracteata*, *Campnosperma coriaceum*, *Combretocarpus rotundatus*, *Ilex cymosa*, *Madhuca motleyana* and *Stemonorus secundiflorus*; commercially important timber species include *Dactylocladus stenostachys*, *Cratoxylum arborescens*, *Gonystylus bancanus, Koompassia malaccensis* and *Shorea* spp*.* A few species have a distribution confined exclusively, or almost so, to peat swamp forest, for example, *D. stenostachys*, *G. bancanus*, *Horsfieldia crassifolia*, and *S. teysmanniana*, of which *G. bancanus* and *H. crassifolia* are endangered and protected by law (CITES Appendix III).

Members of the Pandanaceae, which often form a dense ground cover, ferns and insectivorous pitcher plants (Nepenthaceae) also occur. Bryophytes are abundant on the tops of hummocks and on tree bases, but *Sphagnum* spp. are present in marginal drainage areas only and are not associated with peat formation as they are in temperate and boreal regions (Flenley, 1979; Gates, 1915).

4.2.2 Fauna

The base-line information on animal diversity in lowland tropical peat swamps is very limited and has not been related systematically to the different vegetation types. However, several recent studies have highlighted the role that peat swamp forests play in providing habitats for a number of endangered and rare species, especially birds, fish, mammals and reptiles (Silvius et al., 1984; Bennett & Gombek, 1992; Prentice & Parish, 1992; Doody et al., 1997; Page et al., 1997). Of particular importance is the relatively large population of orang utan (*Pongo pygmaeus pygmaeus*) associated with peat swamp forest in Borneo, which provides one of the most important remaining habitats for this endangered primate (Meijaard, 1997; Page *et al.,* 1997; Husson *et al.* 2002: Morrogh-Bernard *et al.* 2003). Other endangered or threatened mammals found in this ecosystem include agile gibbon (*Hylobates agilis*) (Cheyne, 2007; Cheyne et al., 2007), pig-tailed macaque (*Macaca* nemestrina), sun bear (*Helarctos malayanus*), clouded leopard (*Neofelis nebulosa*) and leopard cat (*Felis bengalensis*) (Rieley & Page, 2005).

The avian species diversity is also noteworthy and embraces a number of rare and threatened species, including Storm's stork (*Ciconia stormi*) and white-winged duck (*Cairina scutulata*) which, along with hook-billed bulbul (*Setornis criniger)* and grey-breasted babbler (*Malacopteran albogulare)*, are considered to be more or less restricted to the peat swamp ecosystem of Southeast Asia (Sheldon, 1987; Page et al., 1997; Wibowo et al., 2000).

Other studies have highlighted the role that peat swamp forests play in providing a refuge for other animal groups. For example, the blackwater rivers that drain the peat swamps were once considered to have low fish species diversity and productivity, but this view has changed following the discovery of many new taxa associated with these unique habitats, including the world's smallest species of fish (*Paedocypris progenetia)* which was found in a Sumatran peat swamp (Kottelat and Ng, 1994; Ng et al., 1994). Peat swamp forests, flooded for up to 9 months or more of the year, are breeding grounds for fish that are commercially important in rivers downstream and coastal areas. Other studies have highlighted the role these wetland forests play in providing a refuge for vulnerable species of reptiles, for example, the false gharial (*Tomistoma schlegelii*) (Bezuijn et al., 2004).

4.3 Hydrology

In an undisturbed condition tropical peatlands, with their high water-holding capacity, perform a major function in regulating water in lowland areas. They serve as reservoirs of fresh water, stabilize water levels in rivers and other waterways, reduce storm-flow and maintain low-flow to buffer against saltwater intrusion (Rieley & Page, 2005).

The majority of lowland tropical peat swamps in Indonesia are completely rain-fed (i.e. they are ombrotrophic) and water flow from upstream areas does not enter them (Rieley et al., 1996). Under natural conditions, the water table will rise with rainfall and fall as a result of evapotranspiration (evaporation of water from peat and vegetation) and the outflow of excess water (Takahashi & Yonetani, 1997). The resulting change in storage can be considerable over short periods (days or weeks). Over years, however, this change in storage will be negligible compared to the total in- and outflow. During the wet season, rainfall always exceeds the combination of evaporation and groundwater run-off and the water table rises and may come above the peat surface, often for several months (Ong & Yogeswaran, 1992; Takahashi *et al*. 2002). These wet conditions are favourable for peat accumulation. During drier months of the year, when rain-free periods may last for weeks or even several months during El Nino events, the water level can drop well below the peat surface.

The dome-shaped surface of most lowland tropical peat swamps causes rainwater to drain off to the sides (Figure 1). Compared to upland catchments, these peat swamps have minimal topographic gradients, however, and combined with the dense forest vegetation and ground microtopography of hummocks and hollows this results in slow surface and subsurface water flow towards the adjacent rivers, particularly in undisturbed peatlands.

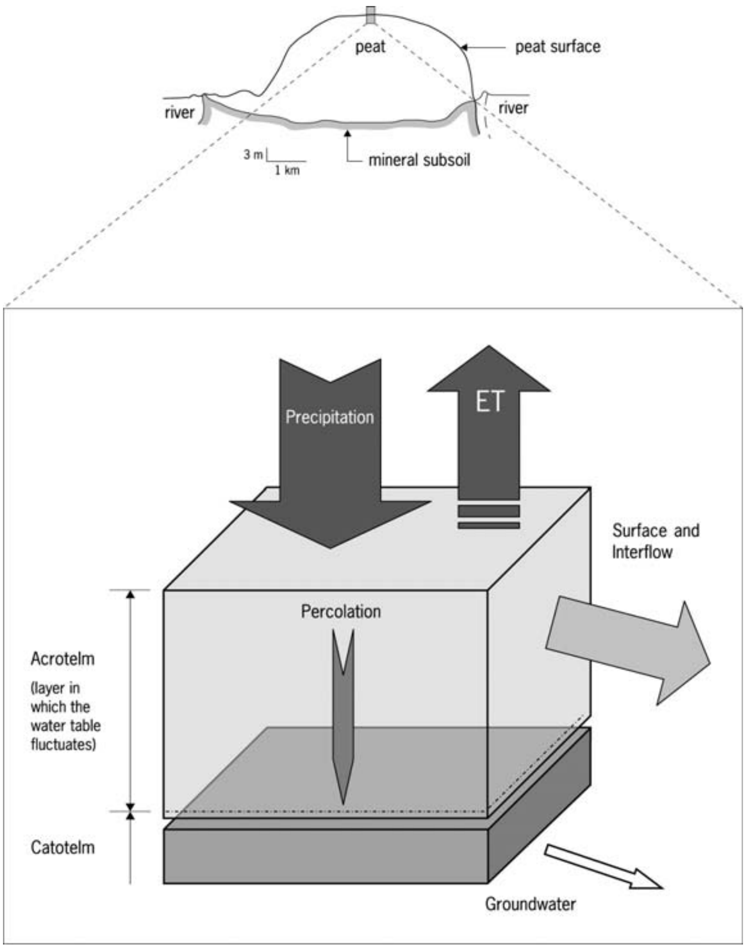


Figure 9: Water balance in a tropical peatland (from Ritzema & Jansen, 2008)

Under tropical conditions daily and annual variation in the amount of rainfall can be considerable, and long periods of extremely low precipitation can lead to temporary drought Wösten et al., 2008). For peat swamps rainfall, in particular that in excess of evaporation is the most important hydrological parameter. The climate of Borneo is characterized by uniform temperature, high humidity and high rainfall. The mean monthly temperature is stable and varies between 24°C and 27°C.

Despite the tropical humid climate, peat swamps can suffer from water shortage during the dry season. In Sarawak, for example, periods with negligible rainfall (<5 mm/week) and a duration of about two weeks occur at least once or twice every year. The average four-week minimum rainfall varies from 50 to 100 mm. This amount is often less than the evapotranspiration, which is around 3 mm d^{-1} (or 84 mm every four weeks). In South Kalimantan, in comparison, the average dry season (weekly rainfall < 25 mm) can last for 3 to 4 months. During this period the rainfall deficit is around 100 mm. In extreme dry years (probability of exceeding = 10%) this period can be extended to seven months, as happened during the 1997 El Nino event. Without water conservation, evaporation can lead to slight but persistent moisture deficits and so to increased oxidation. In very dry years, the water table can fall 1 m below the peat surface.

4.4 Biomass and Nutrient Cycling

A detailed study of the nutrient dynamics of peat swamp forest in the upper Sg. Sabangau catchment indicates that the majority of chemical elements arriving in precipitation (the only source of nutrients) are taken up and retained by the swamp forest trees whilst a small amount is stored in the accumulating peat (Sulistiyanto, 2004). There is an efficient cycling of nutrients within the swamp forest with most of the nutrients that are released as a result of the decomposition of dead vegetation take up again immediately by the tree root systems.

There are differences in above and below ground biomass between peat swamp forest sub-types (biomass is the weight of plants growing in a particular location). The total above-ground forest biomass (woody vegetation plus *Pandanus* spp.) of peat swamp forest in Central Kalimantan varies from 314 t ha^{-1} for marginal mixed swamp forest on peat 2-3 m thick to 252 t ha^{-1} for low canopy pole forest on peat >7 m thick; most of the biomass in both vegetation types is contributed to by trees of diameter $\geq$ 5 cm. Below ground (root) biomass varies from 27 t ha^{-1} for mixed swamp forest to 14 t ha^{-1} for low pole forest, suggesting a trend of decreasing root biomass with increasing peat thickness (Sulistiyanto, 2004). Tree roots are believed to be the principal source of organic matter in an accumulating tropical peat deposit (Brady, 1997a).

4.5 Regeneration of Peat Vegetation and Fire

In the fire- degraded peatland of the ex-MRP area in Central Kalimantan, formerly forested sites subject to a single, low intensity fire subsequently undergo succession to secondary forest, with initial tree species diversity values comparable to those for the adjacent, relatively undisturbed Sabangau peat swamp forest (e.g. 9–16 species of trees compared to 10−14 species per 400 m^2 plot (Page et al., 1999)). With increased frequency and intensity of fire, however, the numbers of tree species and individual trees, saplings and seedlings within the secondary vegetation are greatly reduced, with only two dominant recolonisers, namely *Combretocarpus rotundatus* and *Cratoxylon glaucum*. At the highest levels of degradation, succession back to forest is diverted to a retrogressive succession, in which the plant community becomes more simplistic with fewer species and less biomass. In this situation the vegetation becomes dominated by ferns (*Stenochlaena, Lygodium, Polypodium* and *Pteris* spp.) and sedges (*Cyperus*, *Scleria* and *Thoracostachyum* spp.) with few shrubby trees (Hoscilo et al., 2008). There is very little evidence for fire resistance in peat swamp forest tree species and may be a reflection of the former low incidence of fire in the humid tropical forest biome. Fire kills a large number of trees outright, either because they lack thick, fire-resistant bark or because peat combustion leads to root instability so that otherwise undamaged trees fall over. The loss of canopy trees removes a source of seeds and vegetative propagules, although some species, such as *Barringtonia racemosa*, have been observed to resprout from remnant trunks and roots, even after several fires (observations in Jambi by van Eijk and Leenman 2004).

Thus, increased fire frequency changes the original, undisturbed forest vegetation, which was at low risk of fire, to secondary, fire-prone vegetation that dries out quickly and burns more easily, creating a positive feedback through increased flammability. If this cycle is repeated two or three times, woody species disappear completely. Recent geochemical data (Wüst, unpublished) indicate that fire burns away the small pool of inorganic nutrients which is concentrated in the near-surface section of the peat profile. Fire-induced nutrient depletion is, therefore, a further barrier to post-fire vegetation recovery, although the exact nature of the response is still at an early stage of investigation.

In fire-degraded areas there is also an inter-relationship between ecology and hydrology, in particular the frequency and duration of surface flooding, which have been identified as additional factors in post-fire vegetation succession. The causes of post-fire flooding are: (i) a reduction in the vegetation cover which lowers the transpiration rate and encourages an increase in depth and duration of surface water during the wet season; (ii) subsidence, i.e. lowering of the peat surface, as a result of peat oxidation and combustion; and (iii) alteration of the physical properties of the burnt peat, which has a reduced capacity to store water (hydrophobic). In areas that have frequent wet season flooding of long duration, tree re-establishment is prevented and the vegetation is dominated by non-woody, flood-tolerant species of fern. In locations where there have been repeated fires and substantial combustive loss of peat, i.e. surface subsidence, there is near constant, deep flooding, which creates an open, species-poor, lake-like habitat in which a return to forest vegetation is virtually impossible, at least in the short to medium term. Ironically, areas that are subject to flooding are still at high risk of fire during periods of prolonged drought, since the fern dominated vegetation has a high flammability when dry.

In combination, therefore, fire and flood have a strong influence on preventing vegetation recovery. Fire kills a large number of trees and repeat fires prevent regeneration, through loss of vegetative propagules and nutrient depletion, whilst flooding has its greatest influence on the earliest stages of tree growth because tree seedlings are unable to tolerate prolonged periods of inundation alternating with drought as water tables fall to very low levels in the dry season. The principle barriers to regeneration and/or restoration of forest vegetation include vegetative competition (i.e. between tree seedlings and non-woody species such as ferns, sedges etc.), low nutrient availability (especially at sites subject to recurrent fires), altered peat physical characteristics (e.g. changes in bulk density and water/nutrient holding capacity), high light levels in deforested areas, water availability (including drought and flooding effects), lack of mycorrhizae (a beneficial relationship between fungi and the plant root systems which is particularly important in nutrient-poor soils), and both seed abundance and dispersal (loss of forest cover removes the immediate source of seeds whilst seed dispersal by animals (birds, bats, mammals) is greatly reduced with distance from the forest edge) (Laura Graham, pers. comm.). Research on techniques to overcome these barriers is currently underway.

It is clear from the sections above that planning for the ecological restoration of degraded tropical peatland needs to be based on sound scientific theory and knowledge, but it also has to be relevant to local environmental and socio-economic circumstances. This is critical for tropical peatlands, since their degradation has often occurred through the needs of society to develop the land combined with inappropriate management practices, institutional failures and a lack of awareness of the important functions that intact peatland systems can provide. To attempt to restore the peat swamp forest vegetation does not address the issue of *why* it became degraded in the first place; to reinstate previous ecological functions, and go no further, will leave the ecosystem open to the same fate as before. What is required is a multi-faceted approach which combines an understanding of the ecological and social complexities of the location with the type of restoration needed to allow recovery of ecosystem functions, whilst incorporating local needs and wants. If there is no public acceptance of the goals of tropical peatland restoration, then they will almost certainly fail to be achieved for lack of support (Page et al. in press).

5 Peat and the Carbon Cycle

In an undisturbed condition, tropical peatlands form an efficient terrestrial carbon sink that has made a significant contribution to global terrestrial carbon storage. Tropical peatlands may account for only 10-12% of the global peatland resource by area but, owing to their considerable thickness and high carbon content, they contain around 50 Gt (16%) of the peat soil carbon store and around 3% of the total soil carbon pool (Rieley et al., 2008).

5.1 Peat and Carbon Accumulation

5.1.1 Historical Rates of Peat and Carbon Accumulation

Carbon allocation rates in tropical peatlands in the past have been considerable (Page et al., 2004). During the Late Pleistocene and early Holocene, the lowland peatlands of Central Kalimantan had very rapid peat, and hence carbon, accumulation rates. These were 2.55 mm yr^{-1} and 92 g C m^{-2} yr^{-1}, respectively, between 8540 and 7820 yrs BP. Other rates of early Holocene peat and carbon accumulation in Central Kalimantan range from 0.3 to 2.4 mm yr^{-1} and 47 to 75 g C m^{-2} yr^{-1}, values that are three to four times higher than accumulation rates reported for this same period in temperate and boreal bogs, which are about 20 to 25 g C m^{-2} yr^{-1} (Neuzil, 1997). From 8590 yrs BP, rates of peat and hence carbon accumulation within the peatlands of Central Kalimantan began to decline, decreasing to 0.23 mm yr^{-1} and 11.0 g C m^{-2} yr^{-1} by 6610 yrs BP which coincides, however, with the main mid to late Holocene peat initiation and accumulation phase of the majority of the coastal peatlands of Southeast Asia.

There are few data available on long-term (apparent) rates of carbon accumulation (LORCA) in tropical peatlands, although knowledge of the rate of carbon accumulation and its change through time is necessary when investigating the carbon cycle in peatlands and its relationship to climate change. The average LORCA value for an inland peat deposit in Central Kalimantan is 56 g C m^{-2} yr^{-1}, which is higher than most values for boreal and temperate peatlands that range between 15 and 26 g C m^{-2} yr^{-1} and 10 to 46 g C m^{-2} yr^{-1}, respectively (Page et al., 2004).

5.1.2 Current Rates of Peat and Carbon Accumulation

In the absence of human intervention, many tropical deposits are currently either accumulating peat or are in a steady state (Sorensen, 1993; Page et al., 2004). The current average accumulation rate for Indonesian peatlands has been estimated to be between 1 and 2 mm yr^{-1}, which is substantially higher than the range of 0.2 to 0.8 mm yr^{-1} obtained for boreal and subarctic peatlands and 0.2 to 1 mm yr^{-1} for temperate peatlands.

Estimates of current carbon accumulation rates per unit area in tropical peatlands are 85 g C m^{-2} yr^{-1} in Central Kalimantan, 74-85 g C m^{-2} yr^{-1} in West Kalimantan and 81 g C m^{-2} yr^{-1} in Riau, Sumatra (Page et al., 2004). Applying this range of accumulation rates (74-85 g C m^{-2} yr^{-1}) to a best estimate of the peatland area in Kalimantan (67,880 km^2) and Indonesia (206,950 km^2) produces potential pre-disturbance carbon sink values of 5.0 – 5.8 and 15.3

- 17.6 Mt yr^{-1} respectively, whilst for all Southeast Asian peatlands (253,204 km^2) the estimated potential carbon sink is 18.7 - 21.5 Mt yr^{-1}. In comparison, the present-day sequestering capacity of global peatlands is estimated to be 40 – 70 Mt C yr^{-1}. In other words, although representing only 10-12% aerial coverage of total global peatlands, tropical peatlands could represent more than 30% of the potential global peatland carbon sink (Rieley et al., 2008). It should be noted, however, that all of these values refer to ***potential*** rather than ***actual*** carbon storage since the carbon sequestration function of large areas of tropical peatland has been reduced greatly by deforestation, drainage, agriculture and fire, all of which convert peatland ecosystems from carbon sinks to carbon sources.

5.2 Tropical Peat and the Global Carbon Cycle

5.2.1 Carbon flux and storage

Carbon dioxide (CO_2) is fixed from the atmosphere in the photosynthesis of green plants, and is released back to the atmosphere in plant and animal respiration, and by micro-organisms in aerobic decomposition of organic matter. Under waterlogged conditions peat formation is promoted and oxidation is suppressed (Jauhiainen, 2005). Some anaerobic decomposition takes place in waterlogged peat by micro-organisms that provide substrates for methanogenic bacteria which produce methane (CH_4). Part of the CH_4 produced usually escapes to the atmosphere but some may be converted, by methanotrophic bacteria to CO_2 that is also released (Rieley et al., 2008). The nature of peat and its hydrology have the greatest influence on carbon gas formation in tropical peatlands. Over the millennia of peat accumulation there has been a net positive carbon balance that is reflected in the thick peat deposits that are characteristic of most tropical peatlands. There have been periods of peat oxidation and degradation in response to past climate changes (particularly periods of low rainfall), which have reduced the peat carbon store but, on re-establishment of wet conditions, peat and hence carbon accumulation have recommenced (Rieley et al., 2004, Page et al., 2006).

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 decrease in the peatland water table, which has implications for carbon release from tropical peatlands under different land management and climate change conditions.

In selectively logged peat swamp forest, tree removal leads to a decline in the organic matter available for incorporation into the peat whilst, in deforested peatland, there is a complete cessation of peat accumulation and carbon storage. The peatland carbon cycle is disrupted even more severely under agricultural cropping. There is little or no input of organic matter into the peat whilst, owing to drainage, peat decomposition rates are high and the peat starts to disappear releasing CO_2 to the atmosphere and contributing to the greenhouse effect (Jauhiainen, 2005; Rieley et al., 2008).

5.2.2 GHG emissions from natural peat swamp forest

Cumulative carbon dioxide fluxes

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 CO_2-C m^{-2} yr^{-1}, and is comparable with emissions of 1200±430 g CO_2-C m^{-2} yr^{-1} in a secondary peat swamp forest in South Kalimantan (Inubushi *et al*., 2003). 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.

Cumulative methane fluxes

Methane formation in peat requires anoxic conditions (waterlogging). Methane (CH_4) flux rates from the peat surface in peat swamp forest are between 0.96 and 8.41 g m^{-2} yr^{-1} (Jauhiainen, 2008; Rieley et al., 2008). These rates are lower than from boreal *Sphagnum*-dominated bogs, which range from 1.84 to 14.10 g CH_4-C m^{-2} yr^{-1}. When the depth of the oxic surface peat layer increases, as a result of low rainfall or drainage, CH_4 is oxidized to CO_2 and emissions decrease to zero. In dry conditions the direction of CH_4 flux can be from the atmosphere into the peat (Melling, 2005b).

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, the total CH_4 emissions (3.52-30.90 g CO_2-e m^{-2} yr^{-1}) represent only 0.1 – 0.8% of the corresponding CO_2 emissions (3493-3892 g CO_2 m^{-2} yr^{-1}) from the ground in undrained forest.

5.2.3 GHG flux rates and cumulative fluxes in degraded tropical peat

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 (Jauhiainen et al, 2005; Hirano et al, 2007) (Figure 9). This area is the location of intensive land development that was carried out between 1996 and 1999 and includes drainage affected selectively logged forest, clear felled about 5 years ago, 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 (Jauhiainen et al., 2005; Rieley et al., 2008).

CO_2 fluxes

The highest annual emission of 1091 g CO_2-C (4000 g CO_2) was recorded in the drained forest (Table 1) where CO_2 flux rates from hummocks were very high even in wet conditions. Annual CO_2 emission in the recovering forest site was slightly lower than in undrained peat swamp forest at 927 g CO_2-C m^{-2} yr^{-1} (3400 g CO_2). There were abundant trees growing at both of these sites, resulting in considerable litter production, so that both decomposition and root respiration were taking place. Annual fluxes in the drainage affected forest site were similar to the undrained forest site because their hydrology was similar. In the drainage affected forest, however, the water table, which was 75 cm below the surface in 2001, fell to much lower levels of -153, -113, -167 and -108 cm in the years from 2002 to 2005, probably as a result of progressive peat degradation. The highest CO_2 emission rates in drainage affected sites occurred where channels were deepest.

The annual CO_2 flux at the agricultural site was considerably lower at 526 g CO_2-C $m^{-2}yr^{-1}$ (1928 g CO_2) than at the other two sites and is about the same as that resulting from annual subsidence of developed tropical peatland in Johor and Sarawak, Malaysia (Wösten et al., 1997). These compare with the higher flux rates obtained for oil palm plantation (1540 g CO_2-C m^{-2} yr^{-1} [5652 g CO_2]) and sago plantation (1110 g CO_2-C m^{-2} yr^{-1} [4074 g CO_2]), which are more than twice as high as those from bare peat at the Central Kalimantan site but are similar to undrained forest peat CO_2 losses.

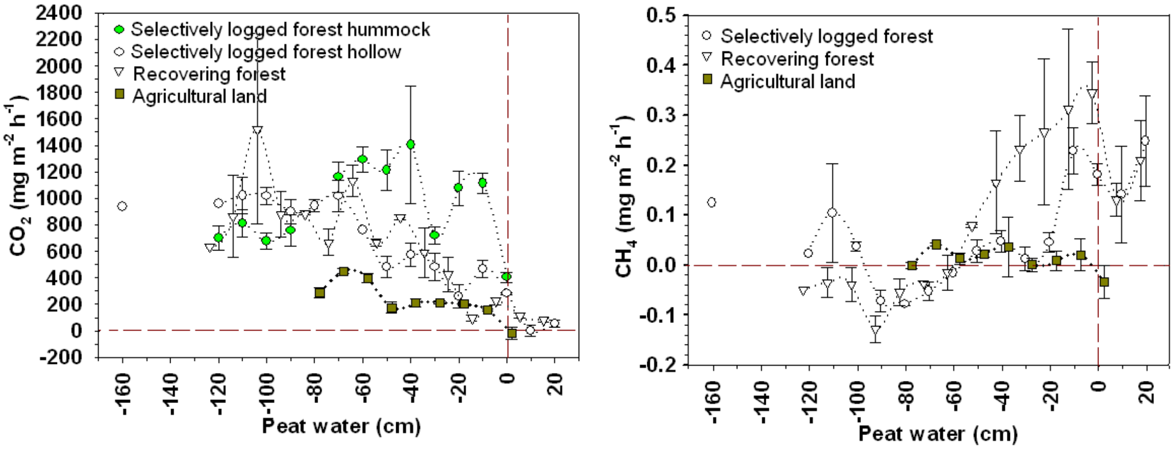


Figure 10: Peat CO_2 fluxes rates (on left) and CH_4 flux rates (on right) at three drainage affected tropical peatland sites (mg m^{-2} h^{-1} with standard error) at various peat water table depth classes. The dotted vertical line shows when the water table is at the peat surface and the horizontal line in the CH_4 graph the zero-flux rate. Note the different scales in the graphs. Based on Jauhiainen *et al.* (2004).

CH_4 fluxes

Following drainage, the volume of peat experiencing oxic conditions increases considerably and the potential for CH_4 oxidation is much greater than in undrained forest. Methane flux rates were greatest in the drainage affected forest hollows and in the recovering forest floor (Figure 2; Table 1). Cumulative annual methane fluxes were highest in the drainage affected forest and recovering forest sites (1.3 and 2.0 g CH_4-C m^{-2} yr^{-1}, Table 1) and are similar to those from undrained forest. At these two sites, peat water table was within 20 cm of the surface for similar periods of about 230 days, but higher annual CH_4 emission occurred in the recovering forest because of more stable water table conditions. At the uncultivated agricultural site the peat was practically CH_4 neutral on an annual basis with a low emission of only 0.09 g CH_4-C m^{-2} yr^{-1} [0.12 g CH_4], which is similar to emissions from grassland (0.073 g CH_4-C m^{-2} yr^{-1}) and vegetable fields (0.046-0.192 g CH_4-C m^{-2} yr^{-1}) in the vicinity (Hatano et al., 2004). Methane fluxes from oil palm and sago plantations in Sarawak, in comparison, were -0.015 g CH_4-C m^{-2} yr^{-1} [-0.02 g CH_4] and 0.18 g CH_4-C m^{-2}

yr^{-1} [0.24 g CH_4], respectively. In these sites, peak CH_4 emissions occurred when the water table was near or above the surface. On the agricultural land, CH_4 flux rates were almost zero at all peat water table depths. The differences in these flux rates can be attributed to a low organic carbon supply from currently growing vegetation and controlled drainage on agricultural land, whereas the abundant vegetation of trees and bushes at the two other sites supplies litter (leaves and branches) continuously to the surface of the peat where it can be consumed by methanogenic bacteria in water saturated (anoxic) conditions with release of CH_4 (Jauhiainen et al., 2005; Rieley et al., 2008).

Table 1: Carbon gas emissions from the peat surface in natural and degraded peat swamp forest in Central Kalimantan, Indonesia. Temporal, cumulative annual CO_2 and CH_4 flux rates (mean with standard error), and total emissions as CO_{2e} global warming potential. Based on data in Jauhiainen *et al*. (2004, 2005).

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

$^{*)}$ 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

$^{**)}$ Numbers for CO_2 are based on 30:70% surface coverage ratio between hummocks and hollows.

5.2.4 Net carbon fluxes on tropical peatland

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. 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 (Rieley et al., 2008).

5.3 Peatlands and Global Carbon

The role and significance of tropical peat to global peat resources and carbon flux and store processes are summarized in Figure 11 and Table 2. This shows the most recent estimates of the amount by area and carbon content that tropical peatlands contribute to the global total. Numerous attempts have been made to estimate the carbon pool in the world's soils and peatlands in particular. These vary widely and are summarized in Immirzi et al., 1992. Until recently, data on tropical peatland area, thickness, volume and carbon content have been insufficient to determine the importance of this carbon store. That deficiency is now changing with the current research interest in tropical peatlands following intensive land use change and a series of disastrous fires.

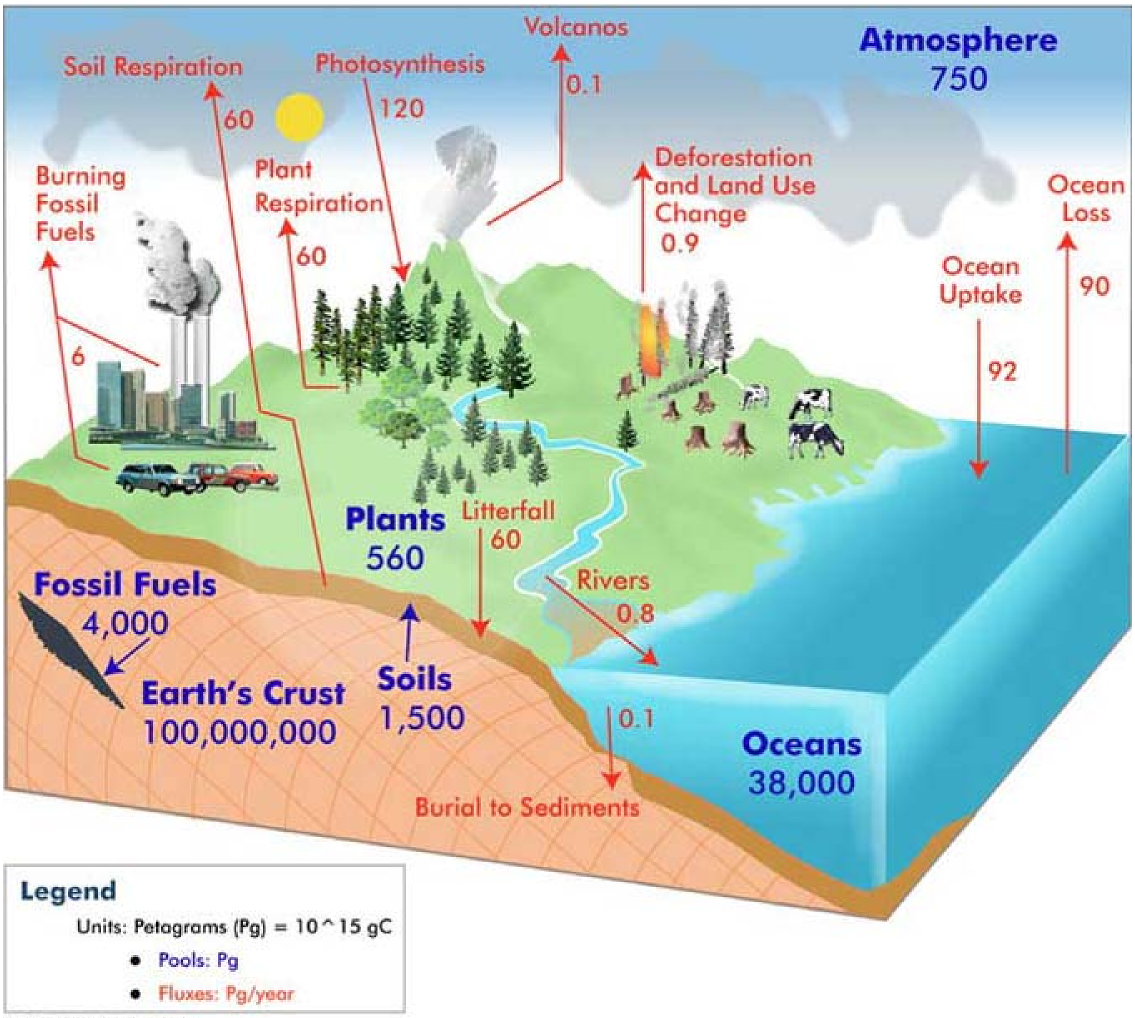


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Figure 11: Diagrammatic representation of global carbon fluxes, sinks and sources. Peatlands, of which tropical peatlands are a significant portion, form part of the carbon store in plants and soil. Tropical peatlands contribute to photosynthetic sinks and respiration losses, although fire losses are also a factor. From http://www.globe.gov/fsl/html/templ.cgi?carboncycleDia&lang=nl&nav=9

Table 2: Contribution of tropical peatland to global peat resources.

Peatland	Area (Mha)	Source	% of global peatland area	Carbon Content (Pg)	% of global peatland carbon	% of global soil C
Global peatland	398.5	1	100	462.0	100	30.8
Tropical peatland	37.7	2	9.5	52.2	11.3	3.5
SE Asia peatland	25.3	3	6.3	50.4	10.9	3.4
EMRP peatland	1.2*	4	0.3	2.7	0.6	0.2

*based on 80% of EMRP is peatland; 1: Immirzi et al, 1992; 2: CARBOPEAT WG1 Report; 3: CARBOPEAT WG1 Report; 4: EMRP Master Plan

6 Socio-Economic Use and Impacts

6.1 Peatland and Livelihoods

Tropical peat swamp forests have been used by local people for millennia for a large variety of life support products and services (Rieley & Page, 2005). Departments of Forestry do not usually regard these non-timber forest resources as anything of value to be conserved and managed in a sustainable way although they form an important component of livelihood subsistence and cash income for people who live near and around peatland areas (Sjarkowi, 2002).

6.1.1 Direct use values in support of peoples' basic needs

Various tradable goods are harvested by people from peatland ecosystems in Central Kalimantan; these are mostly logs and processed timber. Other peat swamp forest products, including rattan, jelutung latex, gemur bark, medicinal plants, charcoal and fire-wood, honey, various inland water fish, frogs and crabs (not to mention some wild species of endangered animals), are traded by local people after being harvested from peatland ecosystems. In order to appreciate the importance of peatland forest resources to existing communities in Central Kalimantan, it is essential to understand the traditional means of livelihood of local inhabitants.

Extractive
This is typified by tapping exhaustible resources, for example, gold mining from a river bed, clay-brick making and stone breaking by using the heat generated by wood fires. These activities are usually complemented by exploiting trees from nearby forest to be used as a source of firewood energy, and therefore doubling the environmental impact of this particular business effort. The work is conducted mostly by transmigrant labourers (Javanese) in conjunction with Dayak or Buginese owners.

Exploitative
This type of business activity depends on the ability to exploit the abundant, but somewhat fixed availability, of biological resources within the peatland ecosystem. Tree cutting and jelutung latex-tapping and gemur bark stripping are examples but forest logging is the most popular. The masterminds of this earning activity are Banjarese people in cooperation with some Dayaks, whilst transmigrants act as labourers.

Explorative
This activity includes harvesting fish or prawns, medicinal herbs or roots, rattan and swamp turtle, which are available in abundance in remote parts of the peat swamp forest ecosystem. These impose minor negative impacts on the ecosystem and have good economic prospects. Many potential resources are still unknown within the peat swamp forest and there is therefore a need for additional research. Indigenous local people together with well-educated Dayaks are very talented in undertaking this kind of business.

Conservative

This is typified by win-win efforts by local people in utilizing the peat swamp forest in environmentally friendly ways. Examples include bee-keeping within a forest site and 'toman' (*Ophiocephalus micropeltes*) fish fattening. The latter is conducted by families taking advantage of kitchen (organic) wastes to feed small wild fish that are caught easily in square nets placed underneath their houses and, in which they are fattened for 10 months until they are large enough to sell.

Intensive

This is a sedentary and more technologically oriented earning effort that is practiced mostly by well-settled transmigrant farmers, although some Dayaks and Banjarese families are also involved. It focuses on intensive fishpond management and associated business. The actual performance is unfortunately impaired by pests and diseases because appropriate technology for peatland agriculture (including aquaculture and animal husbandry) has not been developed so far by local communities.

6.1.2 Socio-economic conditions in peatland areas

Today the lives of local people living within and around peatland ecosystems is constantly being threatened by regional development demands that seek to utilize these ecosystems more profitably. To unorganized smallholders living in rural areas with limited market accessibility and a lack of innovative agribusiness, the remaining (peatland) forest is often considered as a source of land for the next generation to farm. If that occurs there is a strong likelihood of conflict amongst stakeholders over access to forests (natural or planted) for conversion to agriculture. In such a situation people are likely to work on the principle of 'first come, first served' with the result that illegal logging and slash and burn agriculture (including "paddy sonor" farming) would be considered as justifiable livelihood opportunities. It is precisely this scenario that REDD-oriented agroforestry has the potential to prevent. An agroforestry concept called SFMU (social forestry management unit) was introduced (Sjarkowi, 2007) following detailed socio-economic research in Central Kalimantan and South Sumatra. This highlighted the important role of female labour in cash-crop farming (that may potentially support catch crop and tree crop farming). Likewise, from a simple econometric analysis using cross-sectional data, the tendency of male family labour to favour illegal logging over agriculture, was also apparent.

It is important that:

(1) The vicious cycle of rural poverty and forest fire, which is commonly found in degraded peatland ecosystems, could potentially be overcome using REDD-oriented agro-forestry. Food crop and catch crop farming is needed to provide socio-economic support to tree crop farming designed for both income generation and peatland restoration purposes;

(2) Socio-economic approaches are crucial as a means of encouraging local institutions to revitalize peatland ecosystems for the purposes of maintaining various traditional but sustainable livelihoods whilst at the same time improving agro-ecological conditions for the benefit of non-tree crop farming;

(3) As a peatland based agribusiness designed for both socio-economic and socio-ecological purposes, smallholder agro-forestry systems can only be developed effectively when small-scale market-based agro-industry provides added value that will simultaneously help to guarantee fairer and more stable product prices.

6.2 Development Impacts on tropical peatland

Uses of tropical peatland include various types of sector development, for example, agriculture, forestry, mining and urban development, or may involve retention of the natural peat swamp forest ecosystem for community resource provision or wildlife conservation (Rieley & Page, 2005). Unplanned events, including unauthorized (illegal) activities and natural disasters, affect both pristine and sector developed tropical peatlands, often seriously. The former may be illegal logging but could be over exploitation of natural forest products and services that have are under pressure as a result of development, poverty and immigration.

Unexpected natural events of major impact include drought and flood in dry and wet seasons, respectively. As a consequence of climate change it appears that extremes of both are occurring with increasing frequency in the Southeast Asian region. The impacts of these have been exacerbated by inappropriate sector development, for example the ill-fated Mega Rice Project in Central Kalimantan, Indonesia, illegal logging and fire.

Drainage, which is necessary for peatland development, results in rapid peat subsidence within the first 4-10 years (Wösten et al., 1997), followed by a lower constant rate thereafter. Peat physical properties change as a result of subsidence and compaction, especially bulk density increases while total porosity, oxygen diffusion, air capacity, available water volume and water infiltration rate all decrease (Ragjagukguk, 2000). Other problems associated with subsidence are compaction of the peat surface and exposure of buried tree trunks causing problems for cultivation. There is a direct relationship between depth of the water table and rate of subsidence and thus the sustainability of the peat. Thus, in a given area, the choice of a specific land-use option determines the time it will take before either the peat disappears exposing the mineral subsoil, or the drainage base approaches the river level and further drainage by gravity becomes impossible, i.e. the land will flood.

6.2.1 Agriculture

The conversion of tropical peatland for agriculture involves drainage and land clearing that, apart from causing loss of biodiversity, inevitably produces changes in the physical, chemical, and biological properties of the peat soil, introducing constraints for cropping (Widjaja-Adhi, 1997). After drainage and cultivation, peat decomposition continues, leading to progressive subsidence and increasing bulk density. Sustainable agriculture on tropical peatland must optimize crop productivity with minimal peat decomposition (Radjagukguk, 2004). This requires appropriate water management, applied to each crop. The higher the water table the slower the rate of peat decomposition and the longer will be the life of the peatland for agriculture. Excessive drying of the surface peat results in hydrophobicity (water repellency) which renders it much more susceptible to surface waterlogging and erosion. In addition, subsequent cultivation practices will also have an influence on these properties. A deep-rooting crop requires a lower water table than a shallow-rooting crop and, consequently, its cultivation will lead to a higher rate of subsidence and decomposition. Tropical peats are problem soils, which are classified as marginal or unsuitable for crop cultivation. Apart from nutrient deficiencies, there are many other constraints associated with their inherent properties and behaviour, lack of understanding of which has often led to excessive subsidence and rapid exhaustion of the low natural fertility of the peat. In addition to soil and chemical problems, there are also the following (Soepraptohardjo & Driessen, 1976; Notohadiprawiro, 1997):

- The susceptibility to change of the biological, chemical and physical properties of peat following removal of the natural vegetation and drainage leading to:
    - Subsidence
    - Accelerated decomposition of organic matter
    - Desiccation that may develop irreversible hydrophobicity in peat
    - Very strong acidification of peat if it contains enough sulphidic compounds to produce a large amount of sulphuric acid upon acidification
- Extremely rapid horizontal hydraulic conductivity and slow vertical conductivity; the former accelerates the leaching of nutrients while the latter leads to increased flooding
- Very slow upward water conductivity, restricting g the water supply to the rooting zone
- High heat capacity and low thermal conductivity causing, in open space s, large variations in surface temperatures over short distances
- Small effective rooting volume, especially in fibric peats which contain a high percentage of wood
- Low weight bearing capacity, enabling only limited access and causing canopy tree instability
- Irreversible shrinkage that reduces water retention and increases susceptibility to erosion.

High applications of lime and ash result in an excessively high pH, which depresses micronutrient availability but increases microbial activity leading to more rapid peat decomposition. The growth and yield of crops are limited by whichever plant nutrient is the most deficient. If the peat is underlain by pyritic (FeS_2) material, which may be exposed or brought to the surface by canal construction or cultivation (ploughing and ditching), the resulting pyrite oxidation will lead to extreme lowering of the soil pH (to pH 2.0 or less) and acid pollution in waterways. If the underlying material is quartz sand, a complete loss of the peat through oxidation and combustion will render the land unusable because of the almost complete lack of plant nutrient elements, including micronutrients, in this mineral layer.

Growth of crops on tropical peat

Comparison of the yield of various crops on peatland with the national average suggests there is a good prospect of using shallow peatland for growing food crops. With effective water management to maintain the groundwater level at a depth of about 60 cm, pH control, fertilizer addition and adapted crop varieties, perhaps in combination with the surjan system, peatland can be developed into productive farmland. Employing well adapted crops or varieties pH need not be strictly controlled and there is no need for liming; lime may be added only to supply Ca and Mg. The addition of rock phosphate is sufficient to control pH while, at the same time, providing P (Suryanto, 1992). The application of peat ash or wood ash is much better than lime since these not only ameliorate pH, but also increase nutrient uptake considerably, notably of P and K (Suryanto & Lambert, 1992). Irrigation with brackish water is recommended since this has a fertilization effect on coconut plantations in Riau, Sumatra (Notohadiprawiro & Maas, 1991).

Experiments using local varieties of cassava and local and improved varieties of corn on peatland in Barambai, South Kalimantan; cassava yielded an average of 16.6 t ha^{-1} compared to 8-10 t ha-^{1} by farmers in upland fields and the national average of 9.5 t ha^{-1}, whilst corn averaged 0.9 t ha^{-1} (Sihombing & Sebayang, 1986; Brotonegoro et al., 1986). Applying fertilizers, at a rate of N 90, P 45, K 30 kg ha^{-1} and 2 t ha^{-1} of lime, improved the yield of the corn variety Harapan to 1.6 t ha^{-1} the average national yield of which is 1.7 t ha^{-1} (Basa et al., 1986*).*

Observations on peatland at Lunang, West Sumatra, concluded that the duration of reclamation and intensity of water management determined the yield of soybean. With good reclamation and water management, peat of 3-4 m depth can still be made productive for soybean (0.7-1.1 t ha^{-1}) (Taher & Zaini, 1989). The average national yield of soybean is 0.85 t ha^{-1} (Brotonegoro et al.) 1986; Harnoto & Yurida, 1986). In the same area water management played an important role in determining peanut yield, and good harvests were obtained on thick peat (0.9-1.7 t ha^{-1}) (Taher & Zaini, 1989). The average national yield of peanut is 0.98 t ha^{-1} (Brotonegoro et al., 1986; Sutarto et al., 1986).

Peat subsidence

Subsidence is defined as the continuous lowering of the level of the soil surface. Peat soils show characteristically different subsidence behaviour from mineral soils such as clays and sands. Over time, subsidence of mineral soils stops, first with sands and then with clays. Subsidence of peat soils, however, continues over time, albeit at decreasing rates. To understand the complex relationship between total subsidence and drainage, it is useful to divide peat subsidence into three phases, namely consolidation, oxidation, and shrinkage (see Box 2.2). Each of these three phases represents a characteristic behaviour of peat and has different practical consequences for its agricultural use and the environmental issue of CO_2 emission. The initial rapid subsidence occurs because of consolidation. It results in compression of permanently saturated peat layers without a permanent loss of peat. The subsidence rate slows down after the first two years of rapid subsidence (see Figure 3).

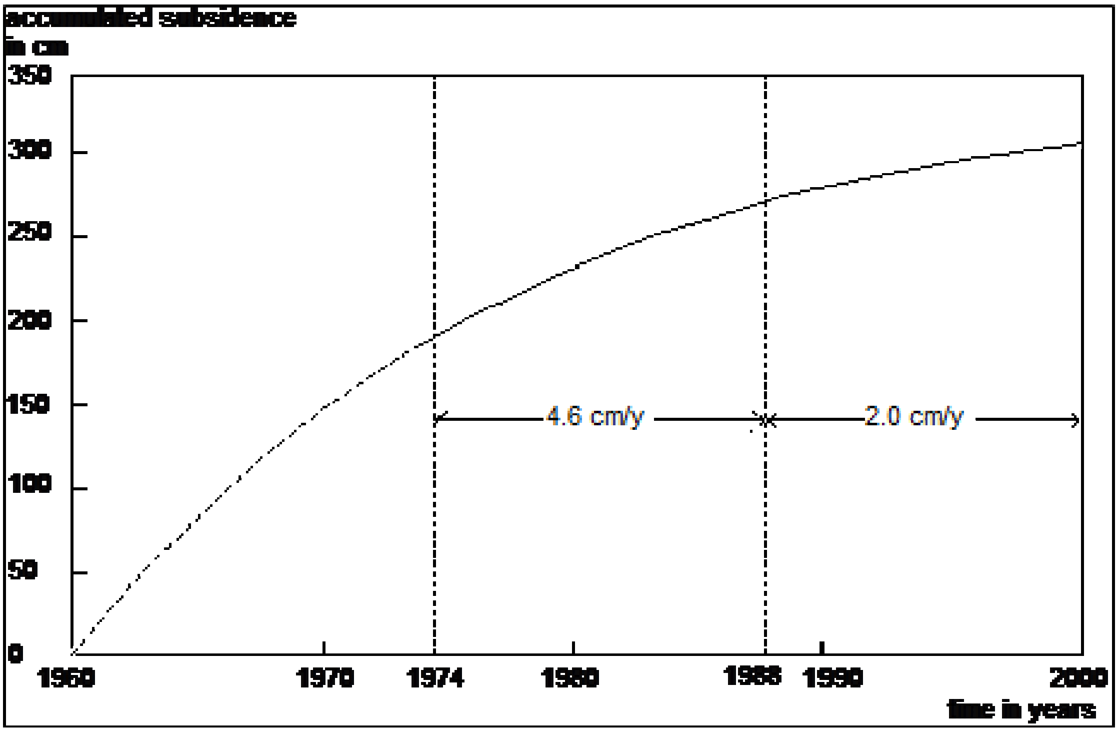

Figure 12: Average subsidence versus time relationship for Western Johor (DID, 2002).

In Western Johor, the first subsidence recordings started in 1974, so no measured data are available on the initial, rapid subsidence (dotted line). In the very beginning, when subsidence is mainly from consolidation, it can be as high as 20 – 50 cm yr^{-1}. After these initial high values, the rates for Western Johor decreased from 4.6 to 2 cm yr^{-1}.

Peat subsidence and groundwater level

The relationship between subsidence and the groundwater level is an important tool for converting optimal groundwater levels, as dictated by different land use options, into subsidence rates. This combination makes it possible to evaluate the sustainability of various cultivation practices on peat soils. For example, the rate of subsidence of peat under sago cultivation with an optimal water table depth of 25 cm is only half the rate of subsidence of peat under oil palm cultivation with an optimal water table depth of 50 cm (Table 2).

The relationship between subsidence and groundwater level follows the equation:

Peat subsidence rate *(cm yr^{-1})* ***= 0.x * depth of the water table*** *(cm).*

The actual co-efficient value (0.x in the general form) depends on the peat characteristics, and it has been found to vary between 0.1 − 0.04 in Sarawak and Western Johor (Wösten *et al.*, 1997). The equation can be used as a tool for converting the optimal groundwater levels, as dictated by the different land-use options, into subsidence rates. With the equation it is possible to combine subsidence rates with the thickness of peat layers to assess the time it will take for all of the peat to disappear and the mineral subsoil to surface.

Table 3: Time span (in years) that will elapse until the peat has disappeared and the mineral subsoil is exposed under two different types of cultivation.

Peat depth (cm)	**Elapsed time span (years) for peat disappearance (***	
	Oil palm	**Sago**
Shallow peat (< 150)	< 10	< 20
Anderson 1 (150 –	10 – 20	20 – 40
Anderson 2 (200 –	20 – 30	40 – 60
Anderson 3 (>250):		
250 – 500	30 – 80	60 – 160
500 – 1000	80– 180	160 – 360
1000 – 1500	180 – 280	360 – 560
1500 – 2000	280 – 380	560 – 760
>2000	> 380	> 760
(*In the example it is assumed that there is an initial rapid subsidence owing to consolidation of 1 m in two years and then a subsequent subsidence, according to the subsidence – groundwater level relationship. It is also assumed that the optimal water table depth is 50 cm for oil palm cultivation and 25 cm for sago cultivation.		

Drajad et al. (1986) reported an average subsidence rate of 0.36 cm $month^{-1}$ in a sapric peat deposit 45-63 cm thick at Barambai (South Kalimantan) 12-21 months after reclamation. At Talio (Central Kalimantan) the rate of subsidence in a 180-240 cm thick sapric peat was 0.78 cm month^{-l}, whereas in a hemic-sapric peat, 179-236 cm thick, it was 0.9 cm month^{-l}. It appears that the rate of subsidence is slower the thinner and/ or more decomposed the peat, a feature that has also been reported from Sumatra (Haridjaja & Herudjito, 1979). This may be related to the greater stability of thinner and more decomposed peats, which may be more suitable for agriculture.

6.2.2 Horticulture

Little attention has been paid to peatland use for horticulture, as most of the efforts and available funds have been allocated to using peatland for the growth of staple food crops, especially rice although growing vegetables on lowland peatland is a common practice, particularly amongst the Chinese farmers in West Kalimantan. The water management requirement is quite simple since the level needs to be lowered only 30-45 cm. Chilli can produce a yield as high as 15.1-20.9 t ha^{-1}, cabbage 21.1-22.7 t ha^{-1} and ginger 14.9-16.4 t ha^{-1}. Other vegetables, which can be grown successfully, are spinach, shallots and pepper (Leong, 1992).

6.2.3 Forestry

Peat swamp forests have been subjected to timber and non-timber exploitation (Radjagukguk, 1992). As species regeneration in peat swamp forest is slower than in other forest types, both legal (controlled) and illegal (uncontrolled) logging have had considerable impacts on both peatland forests and the peatland environment. The extent of the impacts differs according to the methods used and intensity of extraction. Most of the logging in peat swamp forest in Central Kalimantan, especially from 1976 to 1996, involved the selective felling of commercial trees for both domestic use and export. The most important timber species exploited in peat swamps were ramin (*Gonystylus bancanus)* and meranti *(Shorea teysmanniana, S. platycarpa, S. uliginosa)*.

Recently, owing to over-exploitation and the expiry of concession licenses, very few logging companies operate in peat swamp forests. In 2002, the Department of Forestry placed a moratorium on the felling of ramin (*Gonystylus bancanus*) and in 2004 it was declared a protected species under the CITES Convention in order to prevent it from becoming extinct. Never the less, illegal logging has replaced concession logging in many remaining peat swamp forests even those inside protected areas.

In spite of the Department of Forestry regulation requiring replanting of saplings to replace trees felled this had virtually no effect on providing sustainability of the peat swamp forest resource. There is no after care of these replacement plants after the first few years and when concession licenses end logging companies have no further obligation in this respect. Many peat swamp forest concessions have been over logged and have become degraded with little prospect of natural recovery. The composition of vegetation in logged peat swamp forest changes drastically and rapidly, and the opened up areas become dominated by shrubs with a dense ground cover of pandans, ferns and sedges. Other impacts of logging practices include: (1) loss of biodiversity, (2) loss of habitat for wildlife, (3) disturbance of the hydrological cycle as a result of canal construction, (4) altered evapotranspiration, (5) increased rates of oxidation and CO_2 release, (6) compaction of the peat, (7) modification of microclimate in the logged-over peatland forest, (8) increased run-off and erosion and (9) reduction in climate stabilization function.

Plantation forestry

In Indonesia, plantations on peatlands commenced in Sumatra using fast-growing species such as *Acacia mangium,* but without success. Attention has now turned to other *Acacia* spp., particularly *Acacia crassicarpa*, but this requires deep drainage to maintain the water table at 80 – 100 cm below the surface for optimum growth. As a consequence, peat oxidation, CO_2 emissions and subsidence have increased. Some attempts are being made to establish plantations of ramin (*Gonystylus* bancanus) and Jelutung (*Dyera* spp.) but no information is available on their success.

6.2.4 Non-sector impacts

In addition to 'planned' sector impacts upon natural tropical peatlands there are also unplanned and unauthorized impacts that are undesirable (Rieley & Page, 2005). These may appear to arise independently of land use planning and management but they are consequences of the failure of these activities to improve the quality of life and livelihoods of local inhabitants. Most important are fire and illegal logging.

Fire

Forest and peatland fires have been a recurring problem in Indonesia since the early 1980s (Brady, 1989) when conversion of peat swamp forest to agricultural use began on a large scale, promoted by the Indonesian Government's transmigration programme and associated large scale peatland development projects (Bechteler & Siegert, 2004; Siegert *et al.*, 2003). Fire is the principal tool of land clearance and is also used to dispose of unwanted vegetation every year during the dry season by small farmers and large plantation owners.

Since peat swamp forest clearance, prior to drainage and cultivation, requires the removal of all of the trees and woody debris remaining after commercial species have been removed, the cheapest and quickest means is to use fire. In the humid tropics this can be carried out only in the dry season that normally does not exceed three months in duration but, in El Niño years, may extend up to 7 months. Fire can easily get out of control with devastating results that become even worse when it spreads into the underlying peat causing the release of large amounts of carbon and other chemical compounds and particulates to the atmosphere (Page et al., 2000, 2002).

This intensive use of fire gives rise to poor environmental conditions, especially 'haze' (smoke combined with fine particles of soot) that affects not only people locally but extends over distances of several thousands of kilometres across the Southeast Asian region. Smoke from the 1997/1998 peat fires in Indonesia was a major contributor to the cloud of haze that enveloped the Southeast Asian region for several months and affected visibility and air quality as far afield as Singapore, Peninsular Malaysia and southern Thailand. Several cities in Kalimantan and Sumatra had less than 50 m visibility during months of dense haze, which led to temporary airport, school and office closures. The haze produced by peatland fires also has serious impacts on human, animal and plant health, as well on the regional economy (Schweithelm, 1999).

Illegal logging

Illegal logging is unauthorized and uncontrolled tree removal by various vested interests, local, national and international that results in the destruction of the forest resource for future generations (Boehm & Siegert, 2002). It also causes severe damage to the peatland landscape because of the extensive networks of small and large canals excavated in order to extract the cut timber. These canals reduce the water retention capacity of the peatland and increase the rate of runoff so that they dry out quicker following rain and may suffer drought conditions in the dry season. This has an impact upon the remaining forest, making it and the underlying peat more susceptible to fire and threatening its carbon sink and making it and the underlying peat more susceptible to fire.

Relationship between illegal logging and fire

A detailed study carried out in Central Kalimantan showed that the rate of reduction of the peat swamp forest area between 1991 and 1997 was approximately 2.0% yr^{-1} as a result mainly of concession logging, and land clearing for small scale farming and plantations (Boehm & Siegert, 2002). Between 1997 and 2000, however, after the logging concessions licenses had expired, the rate of deforestation increased to about 6.5% yr^{-1}, as a result of illegal logging, land clearance associated with the Mega Rice Project and the peatland fires that occurred in 1997. The average rate of forest loss between 1991 and 2000 was about 3.2% yr^{-1} in the six locations studied. This investigation also showed that the logged over area increased by 44% between 1998 and 2000 mostly because of illegal operations. This over-exploitation made the forests more susceptible to fire and considerable damage occurred once more during the extended drought of 2002. It was demonstrated that besides peat drainage, forest disturbance by logging is the major catalyst for fire. A spatio-temporal analysis showed that fire hazard increased significantly in the vicinity of previous logging operations, recently logged forests were much more vulnerable to fire than forests which had been logged five or more years previously, and intensively logged forest suffered more from fire damage than less intensively logged areas (Langner et al., 2007).

7 Conclusions and Research Needs

Much information exists on many aspects of tropical peatland, including classification, hydrology, ecology, biodiversity and the impacts of land use change and fire. Unfortunately, most of this has been collected from only a few locations in different countries, for example, Brunei and Sarawak (Anderson, 1964-83), Sumatra (Brady, 1997) and Central Kalimantan (Rieley & Page, 2005) and there is a lack of spatial and temporal data collected in the EMRP for comparison and confirmation.

It is clear however, that the only truly sustainable use of peatland within the EMRP (and elsewhere) is as near as possible natural peat swamp forest. This ecosystem has evolved over millennia during which tree litter (leaves, woody material and roots) has contributed to peat accumulation while chemical and physical properties of the peat have influenced the biomass and nutrient cycling of the forest growing on top of it. Ecological and hydrological processes in peat swamp forest are in an equilibrium in which inputs of water and plant nutrients are balanced and large amounts are held in ‘store’ within the peat.

Much water is constantly required in order to maintain the waterlogged nature of this ecosystem and to promote the accumulation of peat through reduced decomposition. Changes to the hydrology of peat swamp forest through drainage, either natural through increased seasonality (dry season length) and man-induced (land use change and fire), lead to loss of ecological and hydrological functions, subsidence and degradation. In natural peat swamp forest most of the nutrient capital is stored in the forest biomass (above and below ground) and little is contained in the peat or water draining from the peatland landscape. Productivity of the forest is constrained by the amount of essential nutrients available in any location. Marginal mixed swamp forest has a higher canopy, more strata and larger biomass than low pole forest because the former has a larger supply of nutrients available in the water that flows from the centre of the peatland to the edge. In a different way, the tall interior forest that straddles the peatland watershed between the Sg. Sabangau and Sg. Bulan in the upper Sebangau catchment obtains additional nutrients because peat in that location has been degrading for several thousand years releasing nutrients from the peat store, which are taken up by the trees and reflected in their stature (height, girth and biomass).

7.1 Implications for Management

The implications for agriculture and forestry are clear, namely that deforested, cleared and drained tropical peatland is deficient in most nutrients necessary for crop growth. In addition, drained tropical peat once it dries out is virtually impossible to rewet and becomes hydrophobic and cannot hold enough water to support crop growth in dry seasons, while in periods of high rainfall it is prone to flooding. The lack of nutrients means that peatland used for agriculture must be limed and fertilized but much of what is added becomes bound to the peat owing to its large cation exchange capacity thereby making much of what is added unavailable for crop uptake.

Peat also releases a range of chemical elements (e.g. aluminium, iron, manganese) and organic compounds (humic, fulvic, stearic acids) that are toxic to plants that are unadapted to them (as natural peat swamp forest trees are) and is deficient in several micronutrients (e.g. copper and zinc) without which crops cannot survive. It is possible in theory to mitigate these problems but this is costly and beyond the means of subsistence farmers. The constant use of ameliorants makes the economics of agriculture on tropical peatland uneconomic and unsustainable.

The use of tropical peatland for forestry experiences similar problems. Under ‘sustainable forestry’ management the peat swamp forest is logged ‘selectively’ by removing individuals of certain commercial species of diameter at breast height (dbh) greater than or equal to 50 cm. After the first logging cycle, in theory, the forest must be allowed to regrow for a period of time sufficient to enable the second crop of trees to reach their minimum dbh. In peat swamp forest this has been judged by the Indonesian Department of Forestry to be 35 years, which is the same as for lowland dipterocarp forest on mineral soil. This time is unlikely to be long enough since the growth of trees on peat is much slower than on non-peat soils and it may take 100 years. This has now become academic owing to the upsurge in illegal logging since the collapse of the Suharto regime in 1998 and most of the trees remaining after the official concessionaires ceased their activities in 1996 have now been removed. All trees much less than 50 cm dbh, even saplings, have been illegally extracted from the forests and therefore it is unlikely the peat swamp forest remaining in the EMRP could recover its full canopy cover and biomass in less than 200 years, if ever. The nutrients that would have been available in the tree biomass for cycling back into developing trees following natural death have been removed and the degraded peatland forests are now nutrient deficient and unable to support the regrowth of the former trees unless this nutrient supply is replaced by an alternative one derived from decomposing peat. In addition, logged-over forests are at a high risk of fire and large areas of remnant forest were lost to fire, particularly during the 1997-1998 and 2002 ENSO-related drought events.

The same problems, therefore, will affect attempts at restoration of the EMRP peatland to either rehabilitate it back to peat swamp forest or divert its land use to an interventive economic one such as agriculture or forestry. Based on the above assessment of the situation, rehabilitation of peat swamp forest must be conserved as a very long term activity (several hundreds of years perhaps) while the establishment of fully sustainable agriculture is probably impossible, i.e. agriculture which can be considered both economically and environmentally sustainable. Whichever type of crop management is employed, arable or plantation crops, it will experience the same problems of acidity, toxicity and nutrient deficiency, not to mention drought and flooding. Even if these are overcome by large inputs of costly ameliorants,the peat will still continue to oxidise, decompose and subside until it disappears. This will lead to progressive increases in the severity and duration of alternate flooding and drought with eventual exposure of the underlying mineral substrate that, in the EMRP, will be either nutrient deficient quartz sand or clay or potential acid sulphate soils. In each event the prospects for the future of agriculture and plantations cannot be considered sustainable in the longer-term.

7.2 Uncertainty and Future Research Needs

This scientific review has highlighted gaps in the knowledge base that require further targetted research in order to fill them. This should form the basis for on-going monitoring of the Ex MRP and the success or otherwise of its rehabilitation. The following research needs for rehabilitation and revitalisation of the Ex-Mega Rice Project area are highglighted.

1. **Standardization:** All procedures (classification, inventory, methodology, etc.) need to be evaluated and standardized. Field data should be collected using approved methods and presented in standard formats (units).
2. **Inventory:** Lack of precision in determining peatland area and peat thickness in the EMRP has led to uncertainties in estimating peat volume and carbon content. There needs to be a detailed field investigation and better mapping of peat distribution and thickness in the EMRP. Priority should be given to collection of data from locations that have been under-sampled so far. Occurrence and thickness of peat should be measured in from major rivers at frequent intervals in order to determine where peat cover starts and to determine the boundary of peat of 3 metres thickness.
3. **Classification:** The parameters used for classifying tropical peatland (e.g. location, geomorphology, water source and chemistry, trophic status) and peat (e.g. thickness, ash and organic matter content) should be evaluated and standardized. The relationship between peat types (classification) and underlying substrates should be established more accurately. The usefulness of various classification systems need to be evaluated with respect to the EMRP. In particular:
    - Peatland classification
    - Peat swamp forest type classification
    - Peat typology/classification
4. **Peat age and origin:** The peat in Central Kalimantan originated in different time periods from Late Pleistocene to Late Holocene (>26,000 YBP to <3,000 YBP). This positional relationship between these types has been established only in the upper Sg. Sabangau catchment and much more information needs to be obtained for other peat landscapes in Blocks A, B, C and E of the EMRP. This is important because the physical and chemical characteristics of the peat differ between the major peat types and these will influence the rehabilitation procedures and their likelihood of success.
5. **Pollen, geochemical and radiocarbon analysis:** Studies of peat typology and inventory should be carried out in association with the collection of peat cores from all major peat domes for pollen analysis, geochemical investigation and radiocarbon dating.
6. **Change in peat characteristics:** The large amount of information on the biotic, chemical and physical characteristics of tropical peat following reclamation and the problems for crop growth that abound in the Indonesian and Malaysian literature should be collected and evaluated.
7. **Bulk density and hydraulic conductivity:** Additional studies are urgently needed of bulk density and hydraulic conductivity throughout the EMRP and down a large number of peat cores. The methods used, however, should be appropriate and standardized.

8. **Peat soil, water and plant chemical analysis:** Similar data are required for these using standardized methods and enumeration.
9. **Hydrology:** The hydrological status of tropical peatland needs to be re-evaluated especially in terms of landscape water inputs, outputs and stores together with implications for nutrient flux and carbon dynamics. There must be consistency of approach and standardization.
10. **Biodiversity:** There is a lack of information on the spatial biodiversity of the remaining peat swamp forest in the EMRP. Most of the information collected so far has been from the Natural Laboratory for Peat Swamp Forest in the upper catchment of Sg. Sabangau with a small amount from the northern part of Block C (Kalampangan) of the EMRP. Virtually nothing is known about the biodiversity of the majority of the EMRP area and this should be rectified by a programme of detailed field investigation at appropriate locations. It is also important to collect together unpublished information that may have been obtained by various groups active within this area, i.e. Japanese and Indonesian scientists, BoS, WWF and CKPP. It is important to document the biodiversity in the remaining areas of peat swamp forest and also to determine that in degraded areas in order to build up a dossier of species available for and likely to benefit from restoration activities.
11. **Impacts of land use change and fire (spatial):** More information is required on these aspects throughout the EMRP. The detailed work carried out by Agata Hoscilo, University of Leicester, UK on Block C should be extended to the rest of the EMRP to build up a comprehensive history and current status evaluation as a result of these damaging impacts. These data are also necessary to assist in selecting priority areas of restoration and planning restoration goals.
12. **Impacts of land use change and fire (chemical and physical):** Information is required on the changes that take place to the chemical and physical characteristics of the surface peat following land use change and fire. Raphael Wűst of James Cook University, Australia has carried out some research into changes to peat surface chemistry following repeated fire in Kalampangan (Block C) and this work should be extended to other locations that have been burnt in other blocks since this information will also be a valuable guide to the type of rehabilitation that might be possible in different locations.
13. **Greenhouse gas emissions:** There is an urgent need to standardize methods and units of presentation in this important field of research so that the work of different people can be compared and assessed. Much more data are required across all land use/cover types within the EMRP and especially information is necessary for respiratory uptake.
14. **Peat accumulation:** Information is needed urgently on whether or not and where peat is accumulating within the EMRP. This should be compared with natural peat swamp forest (e.g. in the Natural Laboratory). This knowledge is vital to the debate on whether or not and how much carbon tropical peatland might be actively sequestering. No one has studied this and it is difficult and expensive to carry out.
15. **Socio-economic data:** Much more information is required on the use that local communities make of peat swamp forest, how much of their livelihood is obtained from

this resource and how their incomes are affected when peat swamp forest is removed and/or burned. What are their alternative livelihood sources of income?

16. **Wise use of peatland in the EMRP:** There is a need for 'life cycle' studies of natural and economic uses of peatland within the EMRP, especially, agriculture, forestry and transmigration. Focus should be placed upon carrying capacity of the peatland and adjacent areas together with estimates of the amount of carbon likely to be lost over varying periods of time (10, 25, 50 and 100 years) and the time before peat disappears. There should be an evaluation of the success/failure of all existing transmigration projects on and adjacent to peatland within the EMRP with comparison made to the carrying capacity of the landscape.
17. **Restoration:** Detailed plans should be made for the restoration of priority peatland areas within the EMRP that address their sustainable management and wise use. There needs to be a justification of where, why, what for, how and which stakeholders for each proposed area.
18. **Carbon accounting and payments:** This is a new and important aspect of rehabilitation of the EMRP. This approach needs to be evaluated fully, with methods developed and accredited for REDD and carbon offsetting under CDM and private investment procedures.
19. **Funding:** How much will rehabilitation of the EMRP cost and how will it be paid for?

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ANNEX 1: Tree Species Noted In Profile Diagrams Shown In Figures 5, 6 And 7

Plot 0 - Tree Species

1. *Palaquium ridleyi,* 2. *Diospyros* sp. A, 3. *Calophyllum* sp. A, 4. unknown, 5. *Knema* sp. A, 6. *Diospyros pseudomalabarica,* 7. *Calophyllum lowii,* 8. *Gonystylus bancanus,* 9. *Planchonella* sp. 10. *Palaquium cochlearifolium,* 11. *Planchonella* sp. 12. *Palaquium cochlearifolium,* 13. *Calophyllum lowii* 14. *Garcinia* sp. A, 15. *Knema* sp. B, 16. *Calophyllum* sp. A, 17. *Garcinia* sp. B, 18. asam asam, 19. *Mezzettia leptopoda,* 20. *Mezzettia leptopoda,* 21. *Shorea macrantha,* 22. *Palaquium cochlearifolium,* 23. *Cratoxylon glaucum,* 24. *Planchonella* sp., 25. *Palaquium cochlearifolium,* 26. *belimbing hutan,* 27. *Palaquium cochlearifolium,* 28. *Diospyros* sp. A, 29. *Palaquium cochlearifolium,* 30. *Palaquium cochlearifolium,* 31. *Dactylocladus stenostachys, 32. Xylopia* sp., 33. *Calophyllum* sp. A, 34. *Knema* sp. B, 35. *Combretocarpus rotundatus,* 36. pasir pasir, 37. *Ficus* sp., 38. *Knema* sp. B., 39. *Lithocarpus dasystachys,* 40. *Shorea macrantha,* 41. *Garcinia* sp. A, 42. *Dactylocladus stenostachys,* 43. *Garcinia* sp. B, 44. *Palaquium cochlearifolium,* 45. *Garcinia* sp. B., 46. *Eugenia spicata*, 47. pasir pasir, 48. *Diospyros* sp. A, 49. *Diospyros* sp. A, 50. *Myristica lowiana,* 51. *Palaquium cochlearifolium,* 52. *Garcinia* sp. C, 53. *Palaquium ridleyi,* 54. *Diospyros pseudomalabarica,* 55. *Garcinia* sp. B., 56. *Tristania grandifolia,* 57. *Garcinia* sp. D, 58. *Diospyros* sp. B, 59. *Palaquium cochlearifolium,* 60. *Planchonella* sp., 61. *Diospyros* sp. B, 62. *Planchonella* sp., 63. *Gonystylus bancanus.*

Notes
Diospyros sp. A - gali gali
Diospyros sp. B - arang arang
Garcinia sp. A - medang telor
Garcinia sp. B - manggis manggis
Garcinia sp. C - unknown
Garcinia sp. D - terati
Knema sp A - mendarah
Knema sp. B - mendarah merah

Plot 1 - Tree Species

1. *Palaquium cochlearifolium,* 2. *Shorea macrantha,* 3. *Gonystylus bancanus,* 4. *Calophyllum* sp. A, 5. *Dipterocarpus* sp., 6. *Combretocarpus rotundatus,* 7. *Shorea teysmanniana,* 8. *Dyera costulata,* 9. *Calophyllum* sp. A, 10. *Calophyllum* sp. A, 11. *Knema intermedia,* 12. *Eugenia* sp. A, 13. unknown, 14. *Palaquium cochlearifolium,* 15. *Garcinia* sp. A, 16. *Mezzettia leptopoda,* 17. unknown, 18. unknown, 19. kerandau, 20. kerandau, 21. *Calophyllum* sp. A, 22. *Eugenia* sp. A, *23. Parastemon* sp., 24. *Artocarpus* sp., 25. *Parastemon* sp., 26. *Dipterocarpus* sp., 27. pasir pasir, 28. *Parastemon* sp., 29. *Diospyros* sp. C, 30. *Mezzettia leptopoda,* 31. *Eugenia* sp. b, 32. *Calophyllum* sp. A, 33. sintuk, 34. *Campnosperma coriaceum,* 35. *Calophyllum* sp. A, 36. *Palaquium cochlearifolium,* 37. *Eugenia* sp. A, 38. *Diospyros* sp. C, 39. unknown, 40. *Dipterocarpus* sp., 41. *Diospyros evena,* 42. *Calophyllum lowii,* 43. unknown, 44. *Knema intermedia,* 45. *Planchonella* sp., 46. unknown, 47. *Planchonella* sp., 48. *Calophyllum* sp. A, 49. unknown, 50. unknown, 51. *Calophyllum* sp. A, 52. *Palaquium cochlearifolium, 53. Tetrameristica glabra,* 54. *Dyera polyphylla,* 55. *Diospyros evena,* 56. unknown, 57. unknown, 58. unknown, 59. *Parastemon* sp., 60. *Eugenia spicata,* 61. *Eugenia* sp. A, 62. *Xylopia* sp., 63. *Calophyllum* sp. A, 64. *Diospyros pseudomalabarica,* 65. *Palaquium cochlearifolium.*

Notes
Eugenia sp. A - milas (1)
Eugenia sp. B - milas kuning
Diospyros sp. C - malam malam kuning

Plot 2 - Tree Species

1. Calophyllum sp. A, 2. Shorea sp., 3. *Palaquium ridleyi,* 4. *Palaquium cochlearifolium, 5. Tristania obovata,* 6. dead tree, 7. *Tristania obovata,* 8. *Eugenia spicata,* 9. *Palaquium cochlearifolium, 10. Eugenia* sp. A, 11. *Palaquium cochlearifolium,* 12. unknown, 13. *Calophyllum* sp. A, 14. *Tristania grandifolia,* 15. *Parastemon spicatus,* 16. *Tristania obovata,* 17. *Palaquium cochlearifolium,* 18. *Calophyllum* sp. A, 19. *Eugenia* sp. A, 20. *Calophyllum* sp. A, *21. Shorea* sp., 22. *Combretocarpus rotundatus,* 23. *Combretocarpus rotundatus,* 24. *Calophyllum* sp. A, 25. *Parastemon spicatus,* 26. bakau bakau, 27. *Campnosperma coriaceum,* 28. *Calophyllum* sp. A, 29. *Parastemon spicatus, 30. Combretocarpus rotundatus,* 31. bakau bakau, 32. *Combretocarpus rotundatus,* 33. *Eugenia* sp. A, 34. *Diospyros pseudomalabarica, 35. Eugenia* sp. C, 36. *Tristania obovata,* 37. unknown, 38. *Calophyllum* sp. A, 39. *Palaquium cochlearifolium, 40. Tristania obovata,* 41. *Combretocarpus rotundatus,* 42. *Combretocarpus rotundatus,* 43. *Tristania obovata,* 44. *Palaquium cochlearifolium,* 45. *Xylopia* sp. A, 46. *Calophyllum* sp. A, 47. *Combretocarpus rotundatus,* 48. *Eugenia* sp. A, 49. *Dactylocladus* stenostachys, 50. *Calophyllum* sp. A, 51. *Palaquium cochlearifolium,* 52. *Palaquium cochlearifolium,53. Tristania obovata,* 54. *Palaquium cochlearifolium,* 55. *Mezzettia leptopoda, 56. Xylopia* sp. B, 57. *Vatica* sp., 58. *Parastemon spicatus,* 59. *Calophyllum fragrans, 60. Parastemon spicatus,* 61. *Combretocarpus rotundatus,* 62. *Calophyllum* sp. A, 63. *Calophyllum* sp. A, 64. unknown, 65. *Tristania obovata,* 66. *Combretocarpus rotundatus,* 67. *Palaquium cochlearifolium,* 68. *Mezzettia leptopoda.*

Notes
***Eugenia* sp. A - milas (1)**
Eugenia sp. C - jambu jambu
Xylopia sp. A - jangkang merah

Xylopia sp. B - jangkang hijou

Plot 4 – Tree Species

1. *Dactylocladus stenostachys,* 2. *Gonystylus bancanus,* 3. *Calophyllum* sp. A, 4. *Shorea balangiran,* 5. *Calophyllum* sp. A, 6. *Alseodaphne coriacea,* 7. *Combretocarpus rotundatus,* 8. pasir pasir, 9. *Calophyllum* sp.A, 10. *Campnosperma coriaceum,* 11. *Calophyllum* sp. A, 12. *Calophyllum* gp. A. 13. *Calophyllum fragrans,* 14. bakau bakau, 15. unknown. 16. *Combretocarpus rotundatus.* 17. unknown, 18. pasir pasir, 19. *Campnosperma coriaceum,* 20. unknown, 21. *Campnosperma coriaceum,* 22. *Campnosperma coriaceum,* 23. *Calophyllum* sp. A, 24. *Parastemon spicatus,* 25. *Xylopia* sp. A, 26. *Palaquium cochlearifolium,* 27. *Calophyllum* sp. A, 28. *Palaquium cochlearifolium,* 29. *Campnosperma coriaceum,* 30. *Xylopia* sp. B, 31. *Tristania obovata,* 32. *Palaquium cochlearifolium,* 33. *Tristania obovata,* 34. bakau bakau, 35. *Tristania obovata,* 36. *Palaquium cochlearifolium,* 37. *Calophyllum* sp. A, 38. *Shorea teysmanniana,* 39. *Xylopia* sp. B, 40. *Calophyllum* sp. S, 41. *Campnosperma coriaceum,* 42. *Shorea balangiran,* 43. *Calophyllum* sp. A, 44. *Palaquium* gp. A, 45. *Calophyllum* gp. A, 46. *Diospyros evena,* 47. *Garcinia* sp. A. 48. *Calophyllum* sp. A, 49. *Campnosperma coriaceum,* 50. *Palaquium* sp. A, 51. *Tristania obovata,* 52. *Calophyllum* sp. A, 53. *Calophyllum* sp.A, 54. *Myristica lowiana,* 55. bakau bakau, 56. *Calophyllum* sp. A, 57. *Gonystylus bancanus,* 58. *Palaquium* sp.

Plot 5· *Tree Species*

1. *Palaquium* sp. A, 2. *Dipterocarpus* sp. A, 3. *Palaquium* sp. A, 4. *Koompassia malaccensis,* 5. *Eugenia* sp. C, 6. *Eugenia* sp. C, 7. *Mezzettia leptopoda,* 8. *Dipterocarpus* sp. B, 9. *Palaquium* sp. A, 10. *Palaquium* sp. A, 11. *Ternstroemia mangifera,* 12. *Palaquium* sp. A, 13. *Kerandau bukit,* 14. jati jati, 15. *Palaquium* sp. A, 16. *Gonystylus bancanus,* 17. *Palaquium* sp. A, 18. *Horsfieldia* sp., 19. *Palaquium* sp.A, 20. *Palaquium* sp. A, 21. mendarah bukit, 22. tamehas, 23. *Palaquium cochlearifolium,* 24. *Palaquium ridleyi,* 25. *Dipterocarpus* sp. C, 26. *Palaquium* sp. A, 27. bakau bakau, 28. tamehas, 29. pasir pasir, 30, *Vatica* sp. A, 31. *Koompassia malaccensis,* 32. *Eugenia* sp. C, 33. *Garcinia* sp. E, 34. *Palaquium ridleyi,* 35. bakau bakau, 36. *Palaquium ridleyi,* 37. *Shorea* sp. A, 38. *Palaquium* sp. A, 39. kerandau puteh, 40. *Garcinia* sp. B, 41. *Blumeodendron* sp., 42. *Mezzettia leptopoda,* 43. *Koompassia malaccensis,* 44. *Palaquium* sp. A, 45. *Palaquium* sp. A, 46. pasir pasir, 47. *Blumeodendron* sp., 48. *Palaquium* sp. A, 49. *Planchonella* sp., 50. *Eugenia* sp. C, 51. *kerandau hitam,* 52. *Palaquium* sp. A, 53. *Casuarina* sp., 54. *Diospyros evena,* 55. *Palaquium* sp. A

Notes

Dipterocarpus sp. A - keruing merah
Dipterocarpus sp. B - keruing puteh
Dipterocarpus sp. C - keruing bukit
Eugenia sp. C - jambu jambu
Garcinia sp. B - manggis manggis
Garcinia sp. E - manggis hutan
Palaquium sp. A - sante
Shorea sp. A - meranti bangkirai
Vatica sp. A - resak bukit

ANNEX 2: Glossary

Acid sulphate soil: A soil containing pyrite, which upon oxidation will result in very low pH values.

Acidity: A property of (soil) water characterised by a pH below 7.

Acrotelm: The surface layer of a peatland that is above the limit of permanent saturation. In a little damaged bog it refers to the active the layer, comprising the living plant cover, passing onwards into recently died plant material and then into fresh peat. It forms the largely oxygenated surface layer with high hydraulic conductivity, within which the water table fluctuates and the main water movement occurs.

Adat: traditional rights of indigenous peoples

Ash content: Weight of a volume of peat after it has been burned.

Bearing capacity: The ability of the soil to sustain a certain load.

Biodiversity: The frequency and variety of living organisms found within a specified geographic region

Biomass: total weight, volume or energy equivalent of organisms in a given area

Biorights: an initiative to create a financial system which will pay people to protect their natural resources and to develop sustainable ways of using them

Biosphere: The part of a planet and its atmosphere in which living organisms exist or that is capable of supporting life

Blackwater: water rich in humic acids and with low nutrient concentrations

Bog: general term for ombrotrophic mires

Bulk density: The mass of soil per unit volume in an undisturbed condition. Normally equivalent to the dry bulk density (i.e. when only the dry soil mass is considered), but sometimes to the wet bulk density (i.e. when the mass of water present is also considered).

Carbon trading: see emissions trading.

Catchment: the entire area drained by a natural stream or artificial drain in such a way that all flow originating in the area is discharged through a single outlet.

Catena: a sequence of soil types and their vegetation that is repeated in a corresponding sequence of topographical sites.

Cation exchange capacity: the extent to which exchangeable cations can be held in a soil.

Catotelm: the lower "inert" layer of the peat of an undamaged ombrotrophic bog. The catotelm underlies the acrotelm, and is permanently water saturated, mainly anoxic and of low hydraulic conductivity.

Compaction: the change in soil volume produced artificially by momentary load applications such as rolling, tamping, or vibration.

Consolidation: The very rapid subsidence after virgin peat swamps are drained resulting in compression of the permanently saturated peat layers. Consolidation occurs as water and/or air are driven out of the voids in the soil.

Decomposition: metabolic degradation of organic matter into simple organic and inorganic compounds, with consequent liberation of energy

Degraded peatland: Peatland that has been affected by human activity or natural phenomena to such an extent that functioning, products and attributes are reduced along with the capacity to recover.

Drainage: The removal of excess surface and subsurface water from the land to enhance crop growth, including the removal of soluble salts from the soil.

Drainage system: (1) A natural system of streams and/or water bodies by which an area is drained. (2) An artificial system of land forming, surface and subsurface drains, related structures, and pumps (if any), by which excess water is removed from an area.

Ecosystem: A dynamic arrangement of plants and animals with their non-living surroundings of soil, air, water, nutrients, and energy.

Ecotourism: a low impact, culturally sensitive land-use with the potential for generating income for local people

Electrical conductivity: Indirect estimate of the solubility of ions required in plant nutrition, expressed in μS cm^{-1}.

El Niño Southern Oscillation (ENSO): warm ocean current that periodically flows along the western coast of South America, usually forming around December - January.

Emission trading: a market mechanism that allows emitters (countries, companies or facilities) to buy emissions from or sell emissions to other emitters. Emission trading is expected to bring down the costs of meeting emission targets, by allowing those who can achieve reduction less expensively to sell excess reductions (e.g. reductions in excess of those required under some regulations) to those for whom achieving reduction is more costly

Enrichment planting: supplementary tree planting inside a natural forest following logging or natural depletion, in order to increase the potential for future commercial forestry.

ENSO (El Niño Southern Oscillation): temporary reversal of airflows and surface ocean currents in the equatorial Pacific region. This results in abnormal warming of the surface waters off the coast of Peru, and in the disturbance of global weather patterns. This abnormal situation occurs every 2 - 10 years and can last for more than a year.

Environmental impact: The effect on the environment of a certain human interference (e.g. artificial drainage).

Evaluation: The assessment of the degree of success of a planned project or process, often undertaken at a specific moment (e.g. upon completion).

Evaporation: (1) The physical process by which a liquid (or solid) is transformed into the gaseous state. (2) The quantity of water per unit area that is lost as water vapour from a water body, a wet crop, or the soil.

Evapotranspiration: The quantity of water used for transpiration by vegetation and lost by evaporation from the soil.

Excess rainfall: That part of the rain of a given storm which falls at intensities exceeding the soil's infiltration capacity and is thus available for direct runoff.

Fibric peat: relatively young peat that is only partially decomposed, with a fibre content > 66 %. It is characterized by high water retention, low pH, low bulk density, and little ash

Functions: The beneficial effects of one entity upon another entity and which can be studied scientifically.

Greenhouse effect: Gasses such as CO, CO_2, CH_4 and N_2O which enter the upper atmosphere from the soil surface, allow solar radiation of short wavelength to reach the Earth but retain longer wavelength radiation of. This causes warming of the atmosphere.

Groundwater: Water in land beneath the soil surface, under conditions where the pressure in the water is equal to, or greater than, atmospheric pressure, and where all the voids are filled with water.

Gt: 1 Gt -= 1 Petagram (Pt) = 10^{15} grams = 10^{9} metric tons

Habitat: The natural home of a plant or animal.

Haze: Aerial suspension of very fine particles.

Hemic: An intermediate stage of organic matter decomposition. Older and more decomposed than fibric peats, with a fibre content of 33-66%

Histosol: soils whose properties are dominated by their content of organic matter

Humification: Decomposition of the original raw peat, with its many coarse root and tree remnants, into peat with many small, uniform pores.

Hydraulic conductivity: The constant of proportionality in Darcy's Law, defined as the volume of water that will move through a porous medium in unit time, under a unit hydraulic gradient, through a unit area, measured at right angles to the direction of flow.

Hydrological regime: The characteristic behaviour of water in a drainage basin over a period, based on conditions of channels, water and sediment discharge, precipitation, evapotranspiration, subsurface water, pollution, etc.

Hydrophobicity: the tendency of a substance to repel water

Illegal logging: Unauthorized and uncontrolled tree removal by various vested interests, local, national and international that results in the destruction of the forest resource for future generations.

Integrated Catchment Management (ICM): Planning approach that takes into account the impact upon the site of activities taking place elsewhere (e.g. upstream deforestation or mining) and the consequences, especially downstream, of on-site operations (e.g. flooding and ground water recharge).

Irrigation: The supply, distribution and controlled applications of water to agricultural land to improve the cultivation of crops.

Land reclamation: Making land capable of more intensive use by changing its general character: by draining excessively wet land, by recovering submerged land from seas, lakes, and rivers; or by changing its saline, sodic, or acid character.

Last Glacial Maximum (LGM): the time of maximum extent of the ice sheets during the last glaciation (defined as 18,000 ± 1,000 yr B.P. on the radiocarbon scale, equivalent to 21,000 yr. B.P. on the calendar time scale)

Leaching: Removing soluble salts by the passage of water through soil.

Levee: A raised embankment to prevent a river from overflowing. A small ridge or raised area bordering an irrigated field

Litter: dead but undecomposed plant material such as leaves, branches and trunks, found on the forest floor

Mangrove: a tidal salt marsh community dominated by trees and shrubs, many of which produce adventitious aerial roots.

[Average] Mean Sea Level ([A]MSL): The average water level in a tidal area.

Mineral soil: soil with low organic matter content, variously defined as anything up to 30 %.

Mire: peat-producing ecosystems which develop in sites of abundant water supply.

Modelling: The simulation of some physical or abstract phenomenon or system with another system believed to obey the same physical laws or abstract rules of logic, in order to predict the behaviour of the former by experimenting with the latter.

Moisture content: the volumetric water content of a soil.

MRP: the **M**ega **R**ice land development **P**roject that operated in Central Kalimantan from 1996 to 1999 when it was abandoned, see appendix 2.

Natural properties of the ecosystem**:** Those physical, biological or chemical components, such as soil, water, plants, animals and nutrients, and the interactions between them.

Oligotrophic peat: Peat with a low mineral content.

Ombrogenous peat: Peat that depends entirely on rainwater for its growth.

Ombrotrophic: receiving nutrients exclusively from precipitation

Organic soils: Soils with a high content of composed or decomposed organic carbon and a low mineral content.

Outlet: The terminal point of the entire drainage system, where it discharges into a major element of the natural open water system of the region (e.g. river, lake, or sea).

Overland flow: Water flowing over the soil surface towards rills, rivulets, channels, and rivers. It is the main source of direct runoff.

Oxidation: Oxidation is the volume reduction of peat above the groundwater level resulting from loss of organic matter due to decomposition by biochemical processes. It starts as soon as peat becomes unsaturated and air enters. It results in CO_2 emission.

Peat: An organic soil, which contains at least 65% organic matter (less than 35% mineral material), and is at least 0.5 m in depth and 1.0 ha in area.

Permeability: (1) Qualitatively, the quality or state of a porous medium relating to the readiness with which such a medium conducts or transmits fluids. (2) Quantitatively, the specific property governing the rate or readiness with which a porous medium transmits fluids under standard conditions. See also **hydraulic conductivity**.

Pg = Petagram = 10^{15} grams = 10^9 metric tons = 1 Gigatonne

pH: A measure of the hydrogen ion concentration in a solution, expressed as the common logarithm of the reciprocal of the hydrogen ion concentration in gram mol per litre.

Pleistocene: geological epoch dated 1.8-1.6 million to 10,000 BP. During the Pleistocene, the climate fluctuated between cold (glacial) and warm (interglacial) periods, causing a rise and drop of the sea level, due to melting of the glaciers and ice formation.

Pneumatophores: roots rising above the level of water or soil and acting as respiratory organ in some peat swamp forest trees

Pores: See **Voids**.

Porosity: The volume of voids as a fraction of the volume of soil.

ppm, ppmv: for liquids and solids ppm = parts per million = µg/g or mg/kg, for mixtures of gases ppmv = µl/l; the volume mixing ratio ppmv is the ratio of the number of moles of water vapour to the number of moles of dry air contained in the volume V occupied by the mixture.

Precipitation: The total amount of water received from the sky (rain, drizzle, snow, hail, fog, condensation, hoar frost, and rime).

Racial tension: disharmony between people of different ethnic origin, owing to competition for spaces, resources of religion

Rehabilitation: A less specific re-creation of natural resource functions and wildlife interest as compared to restoration.

Restoration: Attempt to return a degraded landscape to its former condition as far as possible.

Return period: The time in which a hydrological event is estimated to re-occur

Runoff: That portion of excess rainfall that becomes overland flow.

Sapric peat: most decomposed type of peat, with a fibre content of < 33 %

Seepage: (1) The slow movement of water through small cracks, pores, or interstices of a material, in or out of a body of surface or subsurface water. (2) The loss of water by infiltration from a canal reservoir or other body of water, or from a field.

Selective cutting (logging): logging technique where only trees that meet specific criteria (such as a minimum harvestable diameter) are harvested.

Shrinkage: Shrinkage is the volume reduction of peat above the groundwater level due to irreversible loss of water at highly negative water pressures.

Soil classification: The organisation of types of soil in a systematic and meaningful way, based on practical characteristics and criteria.

Soil fertility: The capacity of a soil to supply the nutrients needed for the growth of crops.

Soil-water content: The volume of water in a soil as a fraction of the total soil volume. Normally determined by drying a soil sample to a constant weight at a standard temperature. Sometimes expressed as a mass fraction.

Stakeholders: a single individual or a group of individuals that may be affected by, or express a strong interest in, the resources or management of an area A more restrictive definition is individuals or groups that share the ‘risk’ involved in management of an area and who will bear the cost of mismanagement of resources or environmental degradation. An important factor determining the success of stakeholder participation is whether or not stakeholders believe that the natural resources are held in trust for future generations and for other people in the community and elsewhere.

Subsidence: The continuing lowering of the level of the land surface, as a combined effect of (i) compaction and compression; (ii) consolidation; (iii) oxidation; and (iv) shrinkage.

Subsistence living: producing enough food to meet the needs of the farmer/agriculturalist and family, but no cash crops

Sungai: Indonesian for river

Surface drainage: The diversion or orderly removal of excess water from the surface of the land by means of improved natural or constructed channels, supplemented when necessary by the shaping and grading of land surfaces to such channels.

Surface runoff: Water that reaches a stream, large or very small, by travelling over the surface of the soil.

Tg = Teragram = 10^{12} grams = 10^{6} metric tons = 1 billion tonnes

Tidal swamps: A swamp whose water level is influenced by tidal water level fluctuations over a considerable distance.

Topogenous peat: Peat formed under the influence of fluctuating levels of river flood water.

Transmigration: Departure from one's native land to settle in another

Transpiration: The quantity of water evaporating via the cuticle and the stomata of natural vegetation or crop canopy to the outside atmosphere.

Values: Independent entities in their own right.

Voids: Small cavities in the soil, occupied by air or water or both.

Water balance: Equating all inputs and outputs of water, for a volume of soil or for a hydrological area, to the change in storage, over a given period of time.

Waterlogging: The accumulation of excessive water on the soil surface or in the root zone of the soil.

Water management: The planning, monitoring, and administration of water resources for various purposes.

Water quality: A judgement of the chemical, physical, and biological characteristics of water and of its suitability for a particular purpose.

Watershed: See catchment.

Water table: The locus of points at which the pressure in the groundwater is equal to atmospheric pressure. The water table is the upper boundary of groundwater.

Wetlands: Land where the saturation with water is the dominant factor determining the nature of soil development and the types of plant and animal communities living in the soil and on its surface.

Wise use of peatlands: Uses of peatlands for which reasonable people now and in the future will not attribute blame.

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