Chapter 2
Tropical and Subtropical Peats: An Overview

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2.1 Introduction

Peats are frequent in cool temperate and boreal regions, but occur also in tropical and subtropical areas. While the distribution and characteristics of peats at higher latitudes have been well documented, peats at lower latitudes are less known. Unrecorded tropical peat reclamation efforts date back several centuries, as, for instance, the reclamation of coastal soils undertaken by the Dutch in the seventeenth century north of Colombo in Sri Lanka. However, it was not until the late 1890s when Koorders provided the first formal description of tropical peats from the forests of Sumatra (Andriesse 1988). Since this early reference, knowledge on tropical peatlands has made progress but by far not at the same pace as the knowledge on temperate and boreal peatlands. The lack of systematic surveys limits the scope of the updating reviews (Shier 1985). One of the most comprehensive documents on tropical and subtropical peats is from the late 1980s (Andriesse 1988).

This chapter provides an overview of tropical and subtropical peats. After describing worldwide peat extent and distribution, the factors controlling peat formation and development, peat features and peat classification are analyzed. The chapter also addresses issues related with peats and peatlands as resources.

2.2 Peat Extent and Distribution

Our knowledge about the areal extent of nontropical peats is supported by reliable statistics, mainly because of the early importance of peat as a source of energy. For tropical peats, by contrast, it was not until the mid-1900s that their extent became better known (Polak 1950). Statistics are not always directly comparable because they may reflect different acceptations and definitions of peat and peatland. The concept of peat varies from that of true peat that contains 100% organic material to that of organic soil defined on the basis of a combination between percent organic

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matter (organic matter = organic carbon × 1.724) and thickness of the organic horizons. According to Andriesse (1988), organic soils have more than 50% organic matter in the upper 80 cm. For Rieley and Page (2005), organic soils are at least 50 cm thick and contain at least 65% organic matter, while Joosten and Clarke (2002) fix these thresholds at 30 cm thickness and 30% organic material. In Histosols, as defined in the USDA Soil Taxonomy (USDA 1999), the amount of organic matter is at least 20–30% in more than half of the upper 80 cm of the soil. Similarly, the term peatland is frequently used as a generic proxy of concepts which are not strictly synonymous, such as wetland, peatswamp, moor, muskeg, pocosin, bog, marsh, mire, and fen (Andriesse 1988; Joosten and Clarke 2002). Martini et al. (2006b) recognize four basic classes of peatland in nontropical environments: bogs, fens, swamps, and marshes, the first one being ombrotrophic and the others being minerotrophic with additional distinctive attributes based on acidity, type of vegetation cover, and water regime. All types of peatland are wetlands, but not all wetlands are peatlands. The global wetland area is estimated at 5.3–6.4 M km^2 (Matthews and Fung 1987; Lappalainen 1996), while only about 60–75% of this surface is actually covered by peat (Armentano and Menges 1986; Andriesse 1988; Wikipedia 2008).

2.2.1 Peats in Temperate and Boreal Regions

Worldwide, peatlands cover an estimated 4.26 M km^2 (Bord na Mona 1984; Andriesse 1988; Chimner and Ewel 2005; Chimner and Karberg 2008). This represents about 3% of the global land mass. The largest proportions concentrate in the temperate and boreal regions of North America (49%) and Eurasia (42%) (Table 2.1). Russia has the world's largest contiguous peat bog, while Canada has the largest total area of peatland, estimated at 1.7 M km^2 (Wheeler 2003).

A recent update of the areas covered by peat and peat-topped soils in Europe, derived from the 1:1,000,000 European Soil Database covering roughly the EU territory, provides a surface area of 291,600 km^2 (Montanarella et al. 2006).

Table 2.1 Worldwide distribution of peatlands

Continent	km^2	%
North America	2,096,400	49.19
Eastern Europe	1,519,578	35.65
Western Europe	259,862	6.10
Asia	248,865	5.84
South America	61,730	1.45
Africa	48,565	1.14
Central America	25,240	0.59
The Pacific	1,650	0.04
Global peatlands	4,261,890	100.00

Source: Data summarized from Bord na Mona (1984) and Andriesse (1988)

This extent is not substantially higher than the total peat area of 279,440 km^2 estimated by Bord na Mona (1984) for Western and Eastern Europe together (ex-Soviet Union excluded). In fact, these two figures are not directly comparable because of, among other reasons, recent changes in the territorial configuration of Europe and the inclusion of peat-topped soils (0–30 cm) in the concept of peatland. In spite of that, the updated figure reflects progress made and accuracy achieved in peat mapping using modern information technology. In some cases, peatlands may cover more than 10% of the surface area of individual countries, such as in Finland (30%), Estonia (22%), Ireland (17%), Netherlands (16%), Sweden (16%), Latvia (12%), and United Kingdom (11%). Finland alone concentrates almost one-third of the peat and peat-topped soils in Europe, and Sweden more than a quarter (Montanarella et al. 2006).

2.2.2 Peats in Tropical and Subtropical Regions

From a practical point of view, based on peatland similarities for reclamation and management purposes, Andriesse (1988) sets the boundaries between tropical–subtropical peats and temperate–boreal peats at latitudes 35° North and South. This territorial belt includes Southeast Asia, most of Africa, and a large stretch of the Americas from Florida and North Carolina to southern Brazil and Uruguay.

The most relevant features that distinguish intertropical lowland peats from temperate–boreal ones are surplus rainfall and high temperatures (Andriesse 1988). High temperature, with little diurnal and seasonal variations, accelerates the rate of peat oxidation. Rainfall controls peat hydrology and also has an effect on vegetation type and composition. Peat initiation is mainly a response to substrate waterlogging because of abundant rainfall or flooding by river overflow in areas with impeded drainage. Many tropical peatlands in low-elevation areas are forest-covered peat swamps, and that represents a striking difference with temperate peatlands commonly covered by sedges and moss. In the subtropical areas of the mid-latitudes, surplus rainfall remains important, but the annual temperature regime is more contrasted. Peatlands and peats occurring on highlands within the tropical and subtropical belts, such as, for instance, in Central Africa above 2,000 m elevation, are closer to those of the temperate regions. Worldwide, peat development has taken place over thousands of years converging at the end into the formation of ombrotrophic peat bogs in both temperate and tropical regions.

Compared with the areal importance of peat in temperate and especially in boreal regions, peatlands are much less extensive in tropical and subtropical environments. Only 0.36 M km^2 peatland, or 8.5% of the global 4.26 M km^2, occur in the warm and moist regions of the world, especially in Southeast Asia in the areas surrounding the South China Sea and areas in Papua-New Guinea that together concentrate 68% of the known tropical peats (Immirzi et al. 1992). Other areas with peatlands of some extent are the Caribbean and the basins bordering the Gulf of Mexico, the Amazon basin, and the wet equatorial belt of Africa, especially

Table 2.2 Extent of tropical and subtropical peatlands

Region	km^2	Global %	Tropical %
Southeast Asia	202,600	4.65	56.6
Caribbean	56,700	1.30	15.8
Africa	48,600	1.11	13.6
Amazonia	15,000	0.34	4.2
South China	14,000	0.32	3.9
Other regions	21,100	0.49	5.9
Tropical and subtropical peatlands	358,000	8.21	100.0

Source: Andriesse (1988)

Table 2.3 Areal ranges of tropical peatlands

Region	Minimum km^2	Maximum km^2
Southeast Asia	196,404	332,152
South America	37,136	96,380
Africa	26,607	88,657
Central America	14,465	25,935
Asia (Mainland)	622	6,245
Pacific	190	21,240
Total areas	275,424	570,609

Source: Page et al. (2007)

the depressional areas around the Gulf of Guinea (Table 2.2). Data on peats and peatlands in the tropics and subtropics are much less accurate than those concerning the higher latitudes, mainly because they are derived from small-scale soil maps in which organic soils are frequently mapped in association with poorly drained mineral soils. Andriesse (1988) considers that the extent of organic soils in the Amazon basin and in the wet equatorial belt of Africa is underestimated and that peat deposits in the tropics and subtropics might occupy areas larger than those so far reported.

As soil and land inventories proceed, data on peat extent are becoming more accurate. However, there are still large data gaps and data discrepancies between sources. According to Page et al. (2006), the total area of undeveloped tropical peatland is in the range of 310,000–460,000 km^2, which is about 10–12% of the global peatland extent. Page et al. (2007) computed data from different sources and found that the range between low and high estimates can be considerable (Table 2.3). In the case of Indonesia, for instance, estimates range from 168,000 km^2 (Bord na Mona 1984) to 270,000 km^2 (Jansen et al. 1985) for the same reference period. For the tropics as a whole, peatland area estimates vary roughly from simple to double, between a minimum of 275,424 km^2 and a maximum of 570,609 km^2 (Page et al. 2007) (Table 2.3). Other estimates set the tropical peat surface area closer to 0.5 M km^2 (Immirzi et al. 1992; Lappalainen 1996; Maltby and Proctor 1996). While the knowledge about tropical lowland peats is steadily increasing, tropical highland peats still remain poorly documented. For instance, all papers on tropical peatlands presented at the most recent (2007) international peat congress held in Tullamore, Ireland, deal exclusively with lowland peats (Farrell and Feehan 2008).

In Central and South America as a whole, peatlands cover about 87,000 km^2, representing 2% of the worldwide peat distribution (Table 2.1). The largest part of this extent is in the Caribbean (56,700 km^2) and in Amazonia (15,000 km^2) that together account for 20% of the tropical peatland areas (Table 2.2). A recent estimate (2007) sets the extent of tropical peatlands in South America between a minimum of 37,000 km^2 and a maximum of 96,000 km^2 (Table 2.3). Peats in tropical and subtropical South America are found in a variety of landscapes, including coastal plains (e.g., deltas of the Amazon and Orinoco rivers), inland sedimentary basins (e.g., Llanos in Colombia and Venezuela, Pantanal in Brazil), and highlands (e.g., filled glacial lakes in the Andes, (pseudo-)karstic depressions and other kinds of pond on the Guayana sandstone plateaus and mesetas).

2.3 Peat Formation and Development

Peat formation results from an unbalance between accumulation and decomposition of organic materials. In places where the speed of deposition exceeds the rate of decay, there will be a surplus of organic matter. Deficit of decomposition is caused by insufficient or low biological activity as a consequence of adverse environmental factors, basically excessive acidity and/or prolonged waterlogging causing anaerobic conditions. In tropical lowlands, the fluctuation of the groundwater level, controlled by rainfall and evapotranspiration, has an important effect on peat formation, especially in forest swamps (Ludang et al. 2007). In tropical highlands, lower temperatures slow down the rate of biomass decomposition in contrast to what occurs in the warm-to-hot lowland areas.

2.3.1 Topography and Water Regime

Topography plays an important role in water concentration and in situ retention. Concave, basin-shaped sites favor water accumulation, especially when coupled with rock or soil substrata of low permeability. Such relief types occur in a variety of landscapes, including coastal tidal marshes, inland depressional plains, undulating peneplains, karstic plateaus, volcanic reliefs, and glacial and periglacial mountains, all present in the tropics and subtropics. In temperate and boreal regions, glacial till plains offer the best conditions for peat formation.

Waterlogging is the main factor controlling peat initiation because it allows the colonization by adapted pioneer vegetation and the preservation of at least part of the decay residues. Water concentrates and stagnates in depressional sites where water outflow is less than water inflow so that excess water remains in situ. Water inflow is runoff, ground- and rainfall water, while water outflow includes water exiting through surface outlets, underground flow, and evapotranspiration. The presence of free water over longer periods favors specialized plants to establish, while water stagnation in more or less closed depressions creates an anaerobic environment that prevents the dead vegetation from decomposition or retards it. The activity of decomposing organisms is suppressed in waterlogged conditions (Lappalainen 1996). As a consequence, vegetation debris accumulates as partly decomposed biomass that constitutes the initial stage of primary peat formation. The process of peat inception and histosol formation in waterlogged conditions is termed paludification (Andriesse 1988) or paludization (Buol et al. 1997). As the initial peat mass continues growing, the peat surface rises above the water level retained in the pool, causing secondary peat formation. The top layers tend then to expand beyond the physical limits of the original depression, and the peat mantle may encroach onto the surrounding slopes, leading to tertiary peat formation. In this enlarged peat reservoir, a perched water table forms that is fed only by rainwater, resulting in the formation of ombrogenous peat.

Gore (1983) and Martini et al. (2006b) clearly contrast paludification, the process of colonization of poorly drained landforms by plant communities, with the process of terrestrialization that consists in a gradual overgrowth and infilling of water bodies by the litter of moss and aquatic plant remains. Comparing the shape of pollen isochrones in kettle hole-shaped basins in northeastern Germany, Gaudig et al. (2006) suggest that the peat-forming-upwards mechanism (i.e., paludification) better explains rapid peat formation in the studied mires than the commonly assumed peat-forming-downwards mechanism (i.e., terrestrialization).

When the water balance is largely positive, peat grows vertically and horizontally, covering with peat blankets the surrounding terrain surfaces. This occurs in the cool wet climates of North America and Northern Europe as well as in tropical highlands. It happens also in tropical and subtropical coastal lowlands, with excess rainfall and poor drainage conditions. Otherwise, peat formation remains approximately confined to the configuration and topographic limits of the original basins.

In the tropics, peat is always associated with waterlogged conditions where oxygen is deficient and the underlying substratum is poor in nutrients (Sieffermann et al. 1988). The temperature regime plays a minor role, in contrast to what happens in temperate and boreal regions. However, tropical peat is not exclusively topogenous, and ombrogenous peat in the tropics is not restricted to high elevations. There are large coastal swamps in Indonesia that are covered by ombrogenous peat with its typical dome-shaped relief (Notohadiprawiro 1997).

2.3.2 *Source and Quality of Water*

Water pH controls the types of plant that can adapt and the nature of the organic residues that contribute to peat formation. Low pH water creates oligotrophic conditions, poor in minerals. Neutral pH water favors eutrophic conditions, rich in nutrients. Intermediate conditions are termed mesotrophic. The rate of peat decomposition decreases from eutrophic to oligotrophic environments as biological activity is increasingly inhibited. Often site conditions tend to change over time, as peat grows vertically and gets out of reach of the nutrient-providing substratum and groundwater. As a consequence, conditions switch from originally eutrophic species-diverse to oligotrophic species-poor, with mainly acidity-tolerant plants, frequently endemic. Peats forming on bare rock exposure might show, in their initial stage of development, substantial differences in plant residues according to the mineralogy of the rocks (for instance, siliceous sedimentary versus igneous-metamorphic substrata).

Water reaction depends on the origin of the water that feeds the peat ecosystem. Kulczynski, quoted by Moore and Bellamy (1974), distinguishes several swamp types according to the water source. The rheophilous type is a swamp fed by cation-rich surface and ground flow that collects water running on or permeating the surrounding landscapes. This is frequently the case of the eutrophic peats that develop in tropical and subtropical lowlands exposed to river flooding and avulsion of mineral sediments. When the water source is mainly rainwater, with some contribution of local surface runoff, the swamp type is called ombrophilous. Rainwater has generally low pH and is poor in nutrients, providing the conditions for oligotrophic peat formation. In highlands, peat sites are commonly of the ombrophilous type. Also lowland peatlands become oligotrophic ombrophilous in their later stage of development, when the peat deposit rises above the groundwater level. In transitional swamp types, fed both by some lateral water seepage and by rainwater, peat is mesotrophic.

Peat formation systems that mainly depend on the inflow of nutrient-rich surface runoff and groundwater from upland soils and surrounding landscapes are called topogenous (Andriesse 1988) or minerotrophic (Anderson et al. 2003). Such peats are frequent in tropical and subtropical lowlands, especially in their initial stages of formation. When the peat system relies mainly on rainwater and the recycling of minerals, peat is called ombrogenous (i.e., bog peat). Lowland peats in advanced stages of development and highland peats belong primarily to this type. Peat deposits are generally topogenous in the early stages of formation and become ombrogenous in later stages. This evolution has been documented in the Sarawak Lowlands, Malaysia, by Anderson (1964) and Andriesse (1974).

2.3.3 Geodynamics

Geomorphogenic processes contribute to creating conditions favorable to peat formation, while sometimes also inhibiting it. In tropical and subtropical regions receiving heavy rainfall, flooding, slope instability, and disruption of the drainage network are common features that have influence on peat formation.

Torrential floods carry large amounts of mineral sediments that are trapped in coastal and inland depressions. The seasonal entry of sediments raises the floor of the depressions and favors the outflow of excess water, while the inflow of freshwater allows oxygenation of the organic residues at a rate higher than that of accumulation. Thus, this process inhibits peat formation when it operates repeatedly.

In contrast to the former, peat accumulation is favored when incoming mineral sediments block the drainage system by clogging the natural water outlets or creating barriers. This occurs in landscape units such as delta depressions surrounded by levees, coastal lagoons with plugged outlets, cut-off meander lakes, abandoned stream beds, small tributary valleys blocked by debris, large basins in coastal plains, river valleys without organized drainage network and lacking drainage outlets, moraine lakes in mountains, karstic and pseudokarstic depressions, among others.

Blanket peats on mountain slopes are exposed to scarring, fragmentation or even large dismantlement because of sliding. Sliding is frequent in soligenous peats that become unstable because of sustained water flow along the interface between the rock substratum and the base of the peat mantle and/or because of oversaturation of the peat body upon heavy rainfall. Failures of blanket peats in temperate regions are frequently due to anthropogenic causes, while they are mainly related to natural instability in tropical and subtropical regions where slope peat exploitation is uncommon. It can be argued whether peat failures are likely to become more frequent in response to climate change effects. A study carried out in Northwest Ireland shows that the high frequency of large rainfall events since 1961 did not trigger landslides, because the latter are in fact controlled by slowly changing internal thresholds (Dykes and Kirk 2006; Dykes et al. 2008). Peat flows on hillslopes under forest cover have been reported from Tierra del Fuego, southernmost Argentina, where the triggering mechanisms are heavy snowfalls or earthquakes (Gallart et al. 1994).

2.3.4 Time and Rate of Formation

In temperate and boreal regions, peat started forming after the last glaciation, as glaciers receded and left exposed poorly drained terrains with irregular moraine and glacial till topography that favored the accumulation of water and organic materials. These peat deposits are thus mainly younger than 10,000 years. Similarly in the tropics, change from glacial-induced aridity to a moister and warmer climate triggered peat formation at the beginning of the Holocene. Some early studies on lowland peats report maximum ^{14}C ages of 4,300 BP in Sarawak (Anderson 1964), 4,400 BP in the Everglades of Florida (Lucas 1982), 6,000 BP in the coastal areas of Southeast Asia (Andriesse 1974; Driessen 1977), and 8,000 BP in central Kalimantan, Indonesia (Sieffermann et al. 1988). In general, inland basal peats are older than coastal basal peats, the age of which is worldwide in the range of 5,500–4,000 calBP, reflecting the time at which rising sea levels stabilized. In contrast, peat started forming already in the Late Pleistocene, around 26,000 calBP in an inland peatland of Kalimantan (Page et al. 2004, 2006). In this place, after a period of rapid organic accumulation in the early Holocene (11,000–8,000 calBP), peat formation continued at a slow rate until nowadays (Neuzil 1997). In the Nilgiri hills, a mountain region at more than 2,000 m a.s.l. in southern India, peat formation was dated back to 40,000 ^{14}C BP (Rajagopalan et al. 1997).

Peat studies carried out on intertropical highlands provide a range of peat initiation dates. Peat inception ^{14}C dates go back to ca 3,000 BP in the Ecuadorean Andes (Chimner and Karberg 2008), 4,300 BP on the high-plateau of the Gran Sabana, Venezuela (Rull 1991), 6,000 BP on table-mountain summits in the eastern Guayana Highlands, Venezuela (Schubert and Fritz 1985; Schubert et al. 1994), 7,500 BP on table-mountain summits of the western Guayana Highlands, Venezuela (Zinck et al. 2011), and 10,630 BP at one site in the Chimantá massif, eastern Guayana Highlands (Nogué et al. 2009).

Peat formation during the Holocene has been neither continuous nor linear. Climate change, sliding in slope conditions, disruption of river networks, and changes in sedimentation are some of the factors that usually affect peat deposition and influence the peat accumulation rate. According to Lucas (1982), it takes between 600 and 2,400 years for 1 m peat to form in temperate and boreal conditions, thus at a rate of 0.42–1.67 mm yr^{-1}. Abundant rainfall and high temperature in most tropical and subtropical lowlands stimulate biomass production, although high temperatures also accelerate oxidation and decomposition of the organic matter. According to Anderson (1964), forest peat formation in Sarawak varies from 4.67 mm yr^{-1} in the lower layers to 2.2 mm yr^{-1} in the upper ones. Similarly, Page et al. (2004) provide data on differential rates of peat formation in inland Kalimantan, with rates of $>$2 mm yr^{-1} at the beginning of the Holocene but decreasing to 0.15–0.38 mm yr^{-1} in the mid- and late Holocene.

In the cooler tropical highland conditions, average peat formation rates are in general lower than in the warm moist lowlands: for instance, 0.2–0.3 mm yr^{-1} in the Guayana Highlands at ca 1,000–2,600 m elevation (Rull 1991; Zinck et al. 2011). These figures are close to the average accumulation rates common in subarctic and boreal peatlands, with often less than 0.5 mm yr^{-1} (Gorham 1991). However, higher deposition rates have been reported from some specific places: 1.3 mm yr^{-1} in the Ecuadorean Andes at 3,968 m elevation (Chimner and Karberg 2008), and 1.84 mm yr^{-1} in the Chimantá massif, eastern Guayana Highlands, at 2,700 m elevation (Nogué et al. 2009).

2.3.5 Vegetation

As peat is made of decayed plant residues, vegetation obviously is a main peat formation factor. Distinction between aerated forest peat and anaerobic swamp peat, as proposed by Kurbatov (1968) for cool moist regions, does not hold in the tropics and subtropics where swamps have frequently forest cover, as, for instance, in the Orinoco river delta (Rodriguez 1999; White et al. 2002) or in the coastal lowlands of Southeast Asia (Anderson 1964). In tropical lowland forest swamps, the build-up of peat is often due essentially to the intrinsic properties of the leaves that accumulate and inhibit decomposition rather than to the properties of the swamp site itself, i.e., the acidic, anaerobic, high tannin conditions (Yule and Gomez 2009). In tropical highland peats, usually covered by meadow and shrub vegetation, roots are mainly responsible for biomass accumulation and peat formation (Chimner and Ewel 2005).

Peat profiles are archives recording vegetation change or stability during the time of peat formation. Andriesse (1988) suggests a classical succession of plant associations in a lowland peat swamp, starting at the bottom with floating aquatic plants, algae, and plankton, followed by perennials emerging from shallow water, and then grassy perennials, shrubs, and trees. As peat systems tend to become ombrogenous in later stages of development, thus nutrient-poor and oligotrophic, vegetation is increasingly dominated by acidophilic plants. In coastal swamps of Southeast Asia, Anderson (1964) recognized a succession starting with pioneering mangrove plants, followed by brackish-water communities, and finally replaced by freshwater swamp communities. In highlands, trees are infrequent in peat profile records. The current vegetation types are mainly shrubland on peat forming in drying lakes (glacial or others) and meadows with sedges and reeds on peat forming in lithogenous depressions.

2.3.6 Peat and Climate Change

Peatlands are natural archives that register the paleoenvironmental conditions associated with peat formation, and for that reason they have been used to reconstruct Holocene climate change (Charman and Warner 2002; Martini et al. 2006a). In a recent paper on peat humification and climate change in southeast Alaska, Payne and Blackford (2008) refer to a set of publications that have attempted to infer climate change from the stratigraphy of peat deposits. For that purpose, a variety of climate indicators has been used, including plant macrofossils, testate amoebae, fossil lipids, and isotope ratios. Peat humification analysis, based on estimating the degree of decomposition using alkali extraction and colorimetry, is a widely used technique for paleoclimatic inference from peatlands. This proxy approach has been successfully applied in northern Europe to infer climate change from the degree of peat humification. By contrast, the study carried out by Payne and Blackford (2008), comparing low-resolution peat humification records from several mire sites in southeast Alaska, did not provide strong evidence of climatic forcing of humification in their area. Such studies deducing climate change from peat stratigraphy and degree of humification are less common in tropical and subtropical areas.

Stable isotope ratios of carbon and oxygen can provide valuable paleoclimate records, as they are able to reflect past moisture variations. Based on a $\delta^{13}C$ record spanning the past 20 kyr from peats in the Nilgiri hills at 2,000 m a.s.l., southern India, Sukumar et al. (1993) identified climate shifts corresponding to the last glacial maximum at 18 kyr BP, an arid phase at 6–3.5 kyr BP, and a short wet phase at 0.6 kyr BP. Rajagopalan et al. (1999) measured the stable carbon and oxygen isotope ratios in cellulose of C3 and C4 plants growing on a montane peat bog in the same region of southern India. The mean monthly $\delta^{13}C$ values were found to be significantly related to rainfall, while the $\delta^{18}O$ values revealed to be sensitive to changes in maximum temperature and relative humidity. The authors suggest that plant isotope–climate correlations could be used for reconstructing past temperature and rainfall conditions of the tropics from the isotopic ratios of peat deposits. Using $\delta^{13}C$ ratios, Medina et al. (2011) and Zinck et al. (2011) reached the conclusion that peat vegetation in the Guayana Highlands, southern Venezuela, did not change significantly during the mid- and late Holocene, a fact that could be interpreted as reflecting climate stability during the same period.

Pollen records from peat deposits allow reconstructing past plant communities and inferring, from their succession in time, correlative climate changes. Using peat pollen assemblages from Guayana Highlands, southern Venezuela, Rull (1991) recognized Holocene climate shifts including a dry phase before about 5,000 BP, followed by a moist phase between 4,000 and 2,700 BP. Working in the same region, Nogué et al. (2009) refined the former finding using the pollen record of the Eruoda-tepui in the Chimantá massif. After a long period of about 9,000 years, between 12.7 and 4.3 kyr calBP, showing little peat formation probably because of limited rainfall, perhumid conditions established between 4.3 and 4.0 kyr calBP with high peat accumulation rates. From 4.0 kyr calBP until nowadays, the vegetation at the tepui summit did not change substantially, suggesting the permanence of climatic conditions similar to the present ones.

The use of peat records for inferring Holocene climate changes in the tropics and subtropics is still lagging behind when compared to the development of such studies in temperate and boreal areas. In a recently published volume on the evolution and records of environmental and climate changes in peatlands (Martini et al. 2006a), only one out of 23 contributing papers addresses specifically the tropical peats, restricted to lowlands.

2.4 Features of Peats and Peatlands

Peat material is strongly related to the characteristics of the landscape and landform in which it forms. To some respect, peat and peatland features in tropical and subtropical regions are not fundamentally different from those of temperate–boreal peats. Peat properties and peatland characteristics are commonly used as diagnostic criteria to classify peat and peatlands.

2.4.1 Physical Peat Properties

Differences in organic matter content of organic soils are primarily related to the position of the water table at each site and, in a lesser extent, to the cooler

Table 2.4 Moisture relationships in three kinds of organic material

Moisture parameters (% oven-dry weight)	Fibric	Mesic	Sapric
Maximum moisture holding capacity	1,057	374	289
Water retention 10 kPa	570	193	163
Water retention 33 kPa	378	150	144
Water retention 1,500 kPa	67	84	100

Source: Data summarized from Farnham and Finney (1965)

temperatures in the lower layers of the peat (Moore et al. 2007). Moisture content is an essential peat property as it controls the accumulation and evolution of organic materials. When expressed on an oven-dry weight basis, both the water holding capacity against gravity and the water retention at lower pressure decrease as a function of the stage of peat decomposition, while water retention at higher pressure increases. Farnham and Finney (1965) report on earlier figures that illustrate the difference in moisture relationships between little decomposed fibric, moderately decomposed mesic (i.e., hemic), and well-decomposed sapric materials (Table 2.4). When the same moisture parameters are expressed on a volume basis, water retention figures increase as the degree of decomposition increases. Microporosity that controls water retention is higher in sapric material than in fibric material.

Hydraulic conductivity is influenced by the degree of decomposition and the bulk density of the organic material. Because of the presence of large pores, water moves faster in fibrous material than in more decomposed material. Hydraulic conductivity is a dynamic property that decreases as peat evolves from fibric to hemic to sapric because of decreasing pore space and increasing water retention. Sometimes, horizontal hydraulic conductivity rates are faster than vertical rates because of peat stratification and the flattened way organic residues often settle in peat profiles. This may result in the formation of perched water tables, especially in the later stages of peat development.

Bulk density is a good proxy of several other peat features, in particular the level of compaction and the degree of decomposition. In general, bulk density values are much lower in organic soils than in mineral soils. Bulk density can vary from 0.05 Mg m^{-3} in non or poorly decomposed material up to 0.5 Mg m^{-3} in well-decomposed material (Andriesse 1988). Bulk density values of less than 0.1 Mg m^{-3} in fibric materials and 0.13–0.2 Mg m^{-3} in sapric materials have been reported from lowland peats of Malaysia and Indonesia (Driessen and Rochimah 1976; Tie and Kueh 1979). In most tropical peats, surface layers are more decomposed than the underlying ones, and have thus higher bulk density values. Specific density of solid peat material ranges from 1.26 Mg m^{-3} to 1.80 Mg m^{-3} (Driessen and Rochimah 1976).

Organic soils are sensitive to irreversible drying after exposure to the sun and/or upon drainage and fire. Many peat soils, especially those with low bulk density, are difficult to rewet. The hydrophobic nature of dried peat has been related to different factors that would prevent the reabsorption of water, including the formation of resinous coating upon drying (Coulter 1957), high lignin content in acid peats (Lucas 1982), and the presence of iron coating around the organic particles. Organic soils that are able to rewet after drying experience changes in volume resulting from swelling–shrinking. Volume changes range from 40% in fibric peats to 90% in aquatic peats (Andriesse 1988).

2.4.2 Chemical Peat Properties

In young peats, the water-soluble compounds, including polysaccharides, monosugars, and some tannin, are the first to be washed away upon decomposition. Cellulose and hemicelluloses also decompose easily. As a result, lignin and lignin-derived substances that are fairly resistant to microbial activity constitute the largest part of older peats. Tropical lowland forest peats have frequently reached an advanced stage of development and, for that reason, may contain up to 75% of lignin and lignin-derivates (Andriesse 1988). In lowland peats, especially those of coastal areas, iron, aluminum, sodium, and sulfur can be present in high levels, inherited from the early paludification stage.

Acidity in organic materials varies widely according to the environmental conditions and the stage of peat development. Reaction is neutral in eutrophic peats (pH 6–7), alkaline in brackish-water peats (pH 7–8), and very strongly acid in tidal peats upon oxidation of pyritic materials (pH 2–3). In general, tropical lowland peats are acid to extremely acid (pH 3–4.5). The acidity of peats forming directly on bedrock reflects commonly, at least in the early stage of development, the mineralogical composition of the substratum, with pH being higher on igneous-metamorphic rocks than on sedimentary siliceous rocks. Strongly developed ombrogenous peats are usually oligotrophic, with extremely acid top layers.

Cation exchange capacity (CEC) of organic soils is strongly pH-dependent, but is in general high because of the abundance of hydrophilic colloids, in particular humic acids and hemicelluloses. CEC usually increases as peat develops, because decomposition of the organic material generates increasing amount of lignin-derivates rich in exchange sites. At pH 7, CEC of fibric material is around 100 cmol(+) kg^{-1}, while it is about 200 cmol(+) kg^{-1} in sapric material (Andriesse 1988). Eutrophic peat is usually fully saturated by divalent cations, while in oligotrophic peat CEC is dominated by hydrogen and base saturation values are low.

Organic carbon content increases with increasing decomposition of the organic materials. EKONO (1981) reports organic carbon values of 48–50% in fibric peat, 53–54% in mesic (i.e., hemic) peat, and 58–60% in sapric peat. Since decomposition of the organic material in tropical lowland peats decreases with depth, top layers show usually higher organic carbon values than deeper layers. The loss on ignition is related to the percentage of organic carbon. According to Tie and Lim (1976) working in Sarawak, the ratios of loss on ignition to carbon content were around 2 on average, but they were usually higher in shallow peats (ratio of 4) than in deep peats (ratio of 2.5). Nitrogen levels are higher in surface layers of deep peats than in those of shallow peats, and this is assumed to be related to the concentration of residual nitrogen in lignin as peat continues decomposing (Hardon and Polak 1941). In general, tropical lowland peat derived from rainforest trees has higher lignin and nitrogen contents, and lower ash, carbohydrate, and water-soluble protein contents than those of temperate peat; the organic matter is less biodegradable leading to faster peat accumulation (Notohadiprawiro 1997).

Other chemical substances present in peat material include phosphorus, free lime, and sulfur. Phosphorus content in oligotrophic tropical peats is generally very low, less than 0.04% on average (Andriesse 1988). Phosphorus release may be significant in completely humified peat (Jordan et al. 2007), but limited to the surface layers under flooded conditions (Stêpniewska et al. 2006). In general, tropical peats are also very poor in lime (<0.3%). Eutrophic peats occur only in exceptional situations, provided with calcium carbonate sources (shell deposits, coral reefs, marl, limestone). High sulfur contents, often in the form of pyrite, are comparatively more frequent in the tropics, especially in coastal lowlands (e.g., the Orinoco river delta in Venezuela). Pyrite forms in peatswamps in the presence of brackish water, commonly associated with potential acid sulfate soils. Pyrite oxidation upon exposure to air in drained peatlands causes extreme acidification (pH 2–3).

2.4.3 Biological Activity in Peats

The aerobic conditions that prevail during the initial stage of peat development allow micro-organisms, including actinomycetes, fungi, and bacteria, to rapidly decompose freshly accumulated organic material. As the peat deposit grows, mostly under fairly permanent water table, micro-organisms adapted to anaerobic conditions take over the decomposition process, using oxygen derived from organic material. High temperatures in the tropical lowlands increase significantly microbial activity. Yule and Gomez (2009) suggest that bacteria and fungi must be responsible for leaf breakdown in a peatswamp they studied in Malaysia, because no aquatic invertebrates to ingest leaf material were found. Usually, biological activity decreases with depth. However, acidity-resistant anaerobic bacteria have been found to increase with depth in oligotrophic peats (Andriesse 1988). Microbial decomposition of organic materials contributes to peat subsidence.

The intensity and type of biological activity depend on a variety of factors including the peatland setting, the physical and chemical properties of the peat material, the water regime and the water quality, among others. The acrotelm–catotelm model is an ecohydrological model that aims to account for the multiple interactions between these factors and understand their effect on the functioning of peatlands (Holden 2006). A distinction is made between an upper acrotelm tier, periodically aerated and partly living, and a lower catotelm tier, always water-saturated, impermeable, anaerobic/anoxic, and mostly biologically dead. This diplotelmic system has still to be tested in tropical environment.

2.4.4 Characteristics of Peatlands

Peat forms in sites with physical features that favor the accumulation and preservation of organic material. In this respect, two factors are important, namely, the geomorphic setting and the water regime. Andriesse (1988) provides a list of landscape units that are most likely to promote the accumulation of organic materials and subsequent peat formation in swampy sites, including deltas, coastal basins, lagoons, narrow inland valleys, depressions in major valleys, meander bends, isolated small bottomlands, and atolls.

Peat thickness varies from a few centimeters to several meters, even tens of meters, sometimes over short distance as in the case of soligenous slope peats. Thick peat mantles are usually found in forest-covered low-lying tropical peatlands (i.e., peatswamp forests). For instance, on the west coast of peninsular Malaysia, the thickness of the organic deposits that formed in marine clay depressions varies from less than 3 m to more than 5 m (Hashim and Islam 2008). In Kalimantan, peat thickness varies from 0.3 to 20 m (Anderson 1983). In highland landscapes, deepest peats are usually found in filled lakes.

In initial stages of formation, peat deposits are usually enclosed within the boundaries of a depression. As peat goes on growing, it overlaps the topographic limits of the original site and tends to expand horizontally, forming peat blankets over the surrounding slopes and hillocks. Vertical peat growth results often in dome-shaped peatswamps that are several meters higher than adjacent river floodplains. The micro-topography of the peat cover can be irregular because of the formation of tussocks on the surface of grassy swamps and the presence of aerial roots and shoots in forest peat areas. The relief under the peat mantle is in general concave, but meso- and micro-topography can vary from flat in the case the buried surface is a depositional one, to irregular when the substratum is fractured bedrock.

Due to the presence of organic substances and iron compounds, water in peatswamps is usually brown to black, but clear. Rivers feeding from overflowing peatlands are sometimes called after their dark-colored water, such as, for instance, the Rio Negro which crosses large oligotrophic lowland peats in Venezuela and Brazil. Oligotrophic drainage water is very poor in nutrients and basic cations (<5 ppm) (Andriesse 1988).

2.5 Peat Classification

Peat and peatland have been classified using a variety of criteria, including the topographic setting, current vegetation cover, peat-originating plant communities, physical and chemical peat properties, genetic processes, and soil taxonomy (Andriesse 1988). These classifications have been mainly applied to peats from the boreal and temperate regions, but much less to tropical and subtropical peats.

2.5.1 Classifications Based on Landscape Features

Topography is a key factor for peat initiation and development. A concave depressional setting favors the accumulation of organic material and the concentration of surface runoff and groundwater flow. As the peat deposit grows vertically, it tends to expand from the initial core area to the surrounding landscape. This topographic basis was used to distinguish between raised bogs in bottom areas and blanket bogs on slopes (Hammond 1981).

The current vegetation cover allows separating, at a first level, forest peatswamps that are more frequent in lowlands, especially in coastal basins, from shrubby and grassy peatswamps more frequent in highlands. Nonwoody peats are further subdivided according to the dominant vegetation type, including moss peat (e.g., *Sphagnum* peat), sedge peat (e.g., Cyperaceae peat), reed peat, heath peat, saw-grass peat, among others. Vegetation may have changed during peat development time, and such changes are recorded in the botanical composition of the successive peat layers. In coastal swamps, for instance, organic residues may be derived from mangrove vegetation at the swamp bottom, brackish-water species in intermediate layers, and freshwater plants in the top layers. This can lead to more complex classifications to account for vegetation successions.

2.5.2 Classifications Based on Peat Properties

Chemical properties, basically nutrient availability, help distinguish between nutrient-rich eutrophic peat, moderately rich mesotrophic peat, and nutrient-poor oligotrophic peat. The provision of nutrients is more related to the source and quality of water than to the nature of the peat material itself. Eutrophic peats are enriched in nutrients by overland flow or river flooding, while oligotrophic peats receive only or mainly nutrient-poor rainwater. In the tropics, raised peats in the lowlands but also less developed peats in highlands are dominantly oligotrophic. The concepts of low moor and high moor reflect, in a somehow similar manner, differences in nutrient content as a function of the peat development stage. Low moor is young moor fed by nutrient-rich groundwater, while high moor refers to older raised peat fed mainly by nutrient-poor rainwater.

Physical characteristics implemented for peat classification are essentially based on the degree of decomposition of the organic material. An early classification proposed by Von Post (1924), still used in some countries, recognizes ten decomposition steps, from little decomposed light-colored fibrous peat to well-decomposed dark-colored, colloidal peat. Modern classification systems of organic soils are based on the same principle but use a much lower number of decomposition degrees. For instance, the USDA Soil Taxonomy (USDA 1999, 2006) distinguishes three types of organic material on the basis of fiber content (fc) expressed in volume after rubbing, wet bulk density (bd) in Mg m^{-3}, saturated water content (wc) as percent of oven-dry material, and color. Fibric materials have fc $> 2/3$, bd < 0.1, and wc 850–3,000$^+$. Sapric materials have fc $< 1/6$, bd > 0.2, and wc < 450. In hemic materials, the selected parameters have intermediate values. Using these criteria, organic soils are classified in the order of the Histosols into Folists, Fibrists, Hemists, and Saprists. These classes are further subdivided to account for specific characteristics that may occur or not in tropical and subtropical environments (e.g., Sulfohemists, Sulfihemists, Luvihemists, Cryohemists, and Haplohemists, in the case of the Hemist suborder). In the World Reference Base for Soil Resources (FAO 2006), Histosols are also recognized as a class at the highest level of the classification system. They are further subdivided into a large number of subclasses that reflect not only decompositional ranges of the organic material but also other soil properties and environmental features such as the presence of salt or sulfur, drainage conditions or base saturation, among others.

2.5.3 Multicriteria Classifications

Integrated multicriteria classifications have also been proposed. For instance, the International Peat Society (Kivinen 1980) developed a system which combines some of the properties above analyzed, specifically the botanical composition (distinguishing between moss, sedge, and wood peats), the degree of decomposition (distinguishing between weakly, moderately, and strongly decomposed), and the trophic status (distinguishing between oligotrophic, mesotrophic, and eutrophic). Unfortunately, this kind of classification accounts only for the peat material itself and ignores the features of the physical environment, in particular the geomorphology and hydrology of the peatlands.

Dammon and French (1987) propose a scheme that combines hydrology and geomorphology as basic criteria for classifying bogs. Three categories of bog, each with several classes, are distinguished according to (1) the source of water (ombrotrophic and minerotrophic bogs), (2) the landforms where the bog development occurs (ombrogenous, topogenous, limnogenous, and soligenous bogs), and (3) the landforms produced by the bog (peat bog lake systems, perched water peatland systems, peat bog stream systems, and ombrogenous peatland systems).

Referring specifically to tropical and subtropical peats, Pfadenhauer (1990) makes a basic distinction between peats forming at low and mid-elevations (up to 1,000–1,500 m a.s.l.) and mountain peats (above 1,000 m a.s.l. in the subtropics and above 1,500 m a.s.l. in the tropics). In each of these two categories, several peat classes are recognized on the basis of the current vegetation cover and floristic composition, the nutrient status, and the water regime. Main peat classes occurring in the lowlands and uplands include floating meadows, swampy oligotrophic low peats covered by grasses and sedges, swampy eutrophic low peats covered by grasses and sedges, and forest peats. In the highlands, distinction is made between sedge and grass low peats, *Sphagnum* peats, and cushion bogs.

Most peat classification schemes were developed in boreal and humid temperate regions, and therefore fail recognizing the distinctive features of tropical peats, such as peat texture and ash content. Based on their studies in the Tasek Bera Basin, Malaysia, Wüst et al. (2003) propose a classification framework that combines the morphological fibric, hemic, and sapric classes of the USDA Soil Taxonomy (USDA 1999) with ash and C contents. Organic deposits are defined as having less than 65% ash (i.e., >35% loss on ignition). Four main groups are distinguished on the basis of ash content: peat (0–55%), muck (55–65%), organic-rich soil/sediment (65–80%), and mineral soil/sediment (80–100%). The peat class is further divided into five subclasses spanning from very low to very high ash content.

2.6 Peat and Peatland as Resources

2.6.1 Reclamation and Multipurpose Uses

Indigenous people developed early experience in managing peatlands in a variety of tropical and subtropical areas (e.g., chinampas in Xochimilco and the Patzcuara lake basin in Mexico; raised fields in poorly drained tropical lowlands; abandoned riverbeds filled with organic deposits). For a long time, large-scale reclamation and use of peats were constrained by factors such as poor drainage, low fertility, risk of disease, and inaccessibility (Andriesse 1988). However, because of the need to meet increasing food demands, tropical peatlands are becoming new agricultural frontier areas, increasingly settled by newcomers, small farmers, and entrepreneurs as well, who frequently lack the required experience to manage such problem-soils.

Reclamation requires taking into account not only the peat material itself, but also the topographic, geomorphic, and hydrologic characteristics of the landscape units (peatland or peatswamp) in which peat forms and develops. When using peat for industrial or energy purposes, it might be enough to know and assess the properties of the material. But when peat is meant to be used for farming or to provide environmental services, then the physiographic setting of the peatland plays a role probably not less important than that of the peat material proper.

Peatland is used in agricultural production and peat is used as a source of energy. The vegetation cover of peatlands provides raw materials that are transformed by local people into crafts, artifacts, and goods, such as raffia palm and papyrus from African swamps and timber from coastal forest swamps in Southeast Asia. From an environmental point of view, peats and peatlands perform regulating functions that play a role in the carbon cycle as carbon stocks, in hydrology as water reservoirs and catchment areas for flood mitigation, in the adsorption of heavy metals and organic pollutants, and in the buffering between salt- and freshwater systems in coastal marshes.

The preservation of pristine peatlands and the management of reclaimed peatlands strongly depend on the hydropedological conditions of the site. Ideally, groundwater levels should be maintained between 40 cm below and 100 cm above the peat surface to prevent subsidence and fire. Working in central Kalimantan, Indonesia, Wösten et al. (2008) noticed that the above-mentioned water-level thresholds were altered during dry years. Relatively intact peatland was able to recover from the disturbance, but degraded peatland became more susceptible to fire. Using a hydropedological modeling approach, they produced groundwater-level prediction maps that can be used for fire hazard warning and coordinated land use planning.

So far, peat in its natural state was considered unsuitable for supporting foundations owing to low bearing capacity. However, because of increasing population pressure, especially in Southeast Asia, new settlements are encroaching on peatlands. The reclamation and use of peat soils for construction require special treatments. Based on laboratory experimentation on peat material, Hashim and Islam (2008) have shown that unconfined compressive strength increased significantly after stabilization of peat soil with a mixture of cement–bentonite–sand and that the strength of stabilized columns was reinforced by enlarging the curing time.

2.6.2 Carbon Storage and Potential Release of Greenhouse Gases

Since the inception of peat formation after the last glacial period, about 10–12 kyr ago, considerable amounts of organic material have slowly built up in peatlands. With the current relevance of climate change on the global agenda, the role of peats as carbon stores and the impact of the potential release of greenhouse gases from peatlands are given increasing importance (ClimSoil 2008). Climate warming may cause changes in the balance and annual distribution of rainfall and evapotranspiration that, in turn, will affect peatland productivity and peat decomposition (Alm et al. 1999). However, peatlands are not yet formally included in global climate models and predictions of future climate change (Limpens et al. 2008).

According to early estimates, the world content of carbon in peat deposits ranges from 150 Gt (Moore and Bellamy 1974) to 300 Gt (Sjörs 1980). Maltby and Immirzi (1993) considered that peatlands could store up to 525 Gt of carbon globally. Uncertainty of the estimates depends on the basic assumptions adopted for peat surface area, peat thickness, and peat density (Shimada et al. 2001; Page and Banks 2007). In a recent attempt to estimate the total carbon stored in tropical peatlands, Page et al. (2007) obtained a range of 16.5–68.5 Gt, based on a minimum area of 275,424 km^2 with 1 m peat thickness and a maximum area of 570,609 km^2 with 2 m peat thickness, respectively, and considering in both cases a volumetric carbon density of 60 kg m^{-3}. Jaenicke et al. (2008), taking into account the biconvex shape of the tropical peatlands to determine peat volume, estimate that Indonesian peatlands alone may store at least 55 ± 10 Gt of carbon. Tropical forest swamp peats in particular may store substantial amounts of carbon and function as carbon sink (Buringh 1984; Satrio et al. 2009).

Although carbon sequestration in peats is considerable, it is generally believed that the contribution of peat burning to the global rise in atmospheric CO_2 will remain subordinate to that of other fossil fuels. However, increasing deforestation of tropical lowland peats will generate large carbon dioxide emissions that may negatively influence the global climate. During the 1997 El Niño-driven dry season, peat and forest fires in Indonesia have released to the atmosphere 0.81–2.57 Gt of carbon, a range equivalent to 13–40% of the average annual carbon emissions caused by the burning of fossil fuels worldwide (Page et al. 2002). Once ignited, smoldering peat fires can continue burning for long periods of time, even centuries, propagating through underground peat layers, especially in peatlands that have been artificially drained. In Central Kalimantan, peatland drainage and the change in land cover from forest to secondary vegetation, which is more flammable, have contributed to increase the frequency of peatland fires during the last decade (Hoscilo et al. 2008).

Jauhiainen et al. (2005), studying the carbon fluxes in a tropical ombrotrophic peatland ecosystem in central Kalimatan, Indonesia, show that CO_2 emissions are highest during the dry season when the water table is low. High water table is thus a relevant condition to restrict carbon emissions from the peatland to the atmosphere. Peatland cultivation not only leads to lowering the water table, but also causes subsidence. Hairiah et al. (2001) estimated a subsidence rate of 2.5 cm per year in oil palm plantations on peat soils in Malaysia. Half of the former was attributed to the process of decomposition/respiration of the organic matter that resulted in a C loss to the atmosphere of 10–20 Mg C ha^{-1} yr^{-1}, an amount ten times greater than the losses from upland soils after forest conversion.

2.7 Conclusion

Worldwide, peats and peatlands are increasingly used as agricultural resource, source of energy, water regulation body, biodiversity reservoir, carbon pool, and provider of other environmental services. However, knowledge on tropical peats is still lagging behind when compared to the development of peat and peatland studies in temperate and boreal areas, although considerable progress has been made in mapping tropical peats, identifying their specific characteristics, assessing their use potentials, and calling the attention on their vulnerability. The online journal “Mires and Peat.” jointly published by the International Mire Conservation Group and the International Peat Society, produces yearly volumes since 2006 that so far include one paper concerned with peat in tropical environment. In a recently published volume on the evolution and records of environmental and climate changes in peatlands (Martini et al. 2006a), only one out of 23 contributing papers addresses specifically the tropical lowlands. Tropical lowland peats, extensive in Southeast Asia, have been relatively well documented, while tropical highland and mountain peats have been so far less studied. The present volume on “Peatlands of the Western Guayana Highlands, Venezuela,” is a contribution to the latter.

References

Alm J, Schulman L, Silvola J, Walden J, Nykänen H, Martikainen PJ (1999) Carbon balance of a boreal bog during a year with exceptionally dry summer. Ecology 80:161–174

Anderson JAR (1964) The structure and development of peat swamps of Sarawak and Brunei. J Trop Geogr 18:7–16

Anderson JAR (1983) The tropical peat swamps of western Malaysia. In: Gore AJP (ed) Mires: swamp, bog, fen and moor, B-regional studies. Elsevier, Amsterdam, pp 181–199

Anderson RL, Foster DR, Motzkin G (2003) Integrating lateral expansion into models of peatland development in temperate New England. J Ecol 91:68–76

Andriesse JP (1974) Tropical lowland peats in South-East Asia. Royal Tropical Institute, Department of Agricultural Research, Communication 63, Amsterdam

Andriesse JP (1988) Nature and management of tropical peat soils. FAO Soils Bulletin 59, Food and Agriculture Organization of the United Nations, Rome

Armentano TV, Menges ES (1986) Patterns of change in the carbon balance of organic soil wetlands of the temperate zone. J Ecol 74:755–774

Bord na Mona (1984) Fuel peat in developing countries. Study Report for the World Bank, Dublin

Buol SW, Hole FD, McCracken RJ, Southard RJ (1997) Soil genesis and classification, 4th edn. Iowa State University Press, Ames

Buringh P (1984) Organic carbon in soils of the world. In: Woodwell GM (ed) The role of terrestrial vegetation in the global carbon cycle: measurement by remote sensing. Wiley, New York, pp 91–109

Charman DJ, Warner BG (2002) Peatlands and environmental change. Wiley, London

Chimner RA, Ewel KC (2005) A tropical freshwater wetland. II: production, decomposition and peat formation. Wetland Ecol Manage 13:671–684

Chimner RA, Karberg JM (2008) Long-term carbon accumulation in two tropical mountain peatlands, Andes Mountains, Ecuador. Mires and Peat 3: Art. 4. http://www.mires-and-peat.net/

ClimSoil (2008) Review of existing information on the interrelations between soil and climate change. Final Report. Alterra, Wageningen UR, The Netherlands

Coulter JK (1957) Development of the peat soils in Malaya. Malays Agric J 40:188–199

Dammon AWH, French TW (1987) The ecology of peat bogs of the glaciated northeastern United States. U.S. Fish and Wildlife Service, Biological Report 85 (7.16). Supt. of Documents, Washington DC

Driessen PM (1977) Peat soils. In: Soils and rice. International Rice Research Institute, Philippines

Driessen PM, Rochimah L (1976) The physical properties of lowland peats from Kalimantan and their significance for land suitability appraisal. In: Research on peat and podzolic soils in Indonesia and their potential for agriculture. Soil Research Institute, Bogor

Dykes AP, Kirk KJ (2006) Slope instability and mass movements in peat deposits. In: Martini IP, Martinez-Cortizas A, Chesworth W (eds) Peatlands: evolution and records of environmental and climate changes, vol 9, Developments in earth surface processes. Elsevier, Amsterdam, pp 377–406

Dykes AP, Gunn J, Convery (née Kirk) KJ (2008) Lanslides in blanket peat at Cuilcagh Mountain, northwest Ireland. Geomorphology 102(3–4):325–340

EKONO (1981) Report on energy use of peat. Contribution to U.N. conference on new and renewable sources of energy. Nairobi

FAO (2006) World reference base for soil resources 2006. A framework for international classification, correlation and communication. World Soil Resources Reports 103. FAO, ISRIC and IUSS, Rome

Farnham RS, Finney HR (1965) Classification and properties of organic soils. Adv Agron 17:115–162

Farrell C, Feehan J (eds) (2008) Proceedings of the 13th international peat congress: “After wise use – the future of peatlands”. International Peat Society, Jyväskylä

Gallart F, Clotet-Perarnau N, Bianciotto O, Puigdefàbregas J (1994) Peat soil flows in Bahía del Buen Suceso, Tierra del Fuego (Argentina). Geomorphology 9:235–241

Gaudig G, Couwenberg J, Joosten H (2006) Peat accumulation in kettle holes: bottom up or top down? Mires and Peat 1: Art. 6. http://www.mires-and-peat.net/

Gore AJP (1983) Introduction. In: Gore AJP (ed) Ecosystems of the world – 4A mires: swamp, bog, fen, moor. Elsevier, New York, pp 1–34

Gorham E (1991) Northern peatlands: role in the carbon cycle and probable responses to climatic warming. Ecol Appl 1:182–195

Hairiah K, Sitompul SM, van Noordwijk M, Palm C (2001) Carbon stocks of tropical land use systems as part of the global C balance: effects of forest conversion and options for 'clean development' activities. International Centre for Research in Agroforestry (ICRAF), Southeast Asian Regional Research Programme. Bogor

Hammond RF (1981) The peatlands of Ireland. Soil Survey Bulletin 35. An Foras Taluntais, Dublin

Hardon HJ, Polak B (1941) De chemische samenstelling van enkele venen in Nederlandsch Indië. Landbouw 17:1081–1093

Hashim R, Islam S (2008) A model study to determine engineering properties of peat soil and effect on strength after stabilization. Eur J Sci Res 22(2):205–215

Holden J (2006) Peatland hydrology. In: Martini IP, Martinez-Cortizas A, Chesworth W (eds) Peatlands: evolution and records of environmental and climate changes, vol 9, Developments in earth surface processes. Elsevier, Amsterdam, pp 319–346

Hoscilo A, Page SE, Tansey K (2008) Repeated and extensive fire as the main driver of land cover change in Block C of the former Mega Rice Project. In: Farrell C, Feehan J (eds) Proceedings of the 13th international peat congress: "After wise use – the future of peatlands", vol 1. International Peat Society, Jyväskylä, pp 206–208

Immirzi CP, Maltby E, Clymo RS (1992) The global status of peatlands and their role in carbon cycling. Report 11, Friends of the Earth, London

Jaenicke J, Rieley JO, Mott C, Kimman P, Siegert F (2008) Determination of the amount of carbon stored in Indonesian peatlands. Geoderma 147(3–4):151–158

Jansen JC, Diemont WH, Koenders N (1985) Peat development for power generation in West Kalimantan – an ecological appraisal. The Netherlands Economic Institute, Rotterdam

Jauhiainen J, Takahashi H, Heikkinen JEP, Martikainen PJ, Vasanders H (2005) Carbon fluxes from a tropical peat swamp forest floor. Glob Change Biol 11(10):1788–1797

Joosten H, Clarke D (2002) Wise use of mires and peatlands. International Mire Conservation Group and International Peat Society, Jyväskylä

Jordan S, Velty S, Zeitz J (2007) The influence of degree of peat decomposition on phosphorus binding forms in fens. Mires and Peat 2: Art. 7. http://www.mires-and-peat.net/

Kivinen E (1980) Proposal for general classification of virgin peat. Proceedings of the 6th international peat congress, Duluth, pp 47–51

Kurbatov IM (1968) The question of the genesis of peat and its humic acids. In: Robertson RA (ed) Transactions of the 2nd international peat congress, Leningrad, vol 1. HMSO, Edinburgh, pp 133–137

Lappalainen E (ed) (1996) Global peat resources. International Peat Society, Jyväskylä

Limpens J, Berendse F, Blodau C, Canadell JG, Freeman C, Holden J, Roulet N, Rydin H, Schaepman-Strub G (2008) Peatlands and the carbon cycle: from local processes to global implications – a synthesis. Biogeosciences 5:1475–1491

Lucas RE (1982) Organic soils (Histosols). Formation, distribution, physical and chemical properties and management for crop production. Research Report 435 (Farm Science). Michigan State University, East Lansing, MI

Ludang Y, Jaya A, Inoue T (2007) Geohydrological conditions of the developed peatland in Central Kalimantan. World Appl Sci J 2(3):198–203

Maltby E, Immirzi P (1993) Carbon dynamics in peatlands and other wetland soils: regional and global perspectives. Chemosphere 27:999–1023

Maltby E, Proctor MCF (1996) Peatlands: their nature and role in the biosphere. In: Lappalainen E (ed) Global peat resources. International Peat Society, Jyväskylä, pp 11–19

Martini IP, Martinez-Cortizas A, Chesworth W (eds) (2006a) Peatlands: evolution and records of environmental and climate changes, vol 9, Developments in earth surface processes. Elsevier, Amsterdam

Martini IP, Martinez-Cortizas A, Chesworth W (2006b) Peatlands: a concise guide to the volume. In: Martini IP, Martinez-Cortizas A, Chesworth W (eds) Peatlands: evolution and records of environmental and climate changes, vol 9, Developments in earth surface processes. Elsevier, Amsterdam, pp 1–13

Matthews E, Fung I (1987) Methane emission from natural wetlands: global distribution, area, and environmental characteristics of sources. Glob Biogeochem Cycles 1:61–86

Medina E, Cuevas E, Huber O (2011) Origin of organic matter leading to peat formation in the southeastern Guayana uplands and highlands. In: Zinck JA, Huber O (eds) Peatlands of the Western Guayana Highlands, Venezuela, Chap. 8. Springer, Heidelberg, doi: 10.1007/978-3-642-20138-7_8

Montanarella L, Jones RJA, Hiederer R (2006) The distribution of peatland in Europe. Mires and Peat 1: Art. 1. http://www.mires-and-peat.net/

Moore PD, Bellamy DJ (1974) Peatlands. Elek Science, London

Moore TR, Bubier JL, Bledzki L (2007) Litter decomposition in temperate peatland ecosystems: the effect of substrate and site. Ecosystems 10:949–963

Neuzil SG (1997) Onset and rate of peat and carbon accumulation in four domed ombrogenous peat deposits, Indonesia. In: Rieley JO, Page SE (eds) Biodiversity and sustainability of tropical peatlands. Samara, Cardigan, pp 55–72

Nogué S, Rull V, Montoya E, Huber O, Vegas-Vilarrúbia T (2009) Paleoecology of the Guayana Highlands (northern South America): Holocene pollen record from the Eruoda-tepui in the Chimantá massif. Palaeogeogr Palaeoclimatol Palaeoecol 281:165–173

Notohadiprawiro T (1997) Twenty-five years experience in peatland development for agriculture in Indonesia. In: Rieley JO, Page SE (eds) Biodiversity and sustainability of tropical peatlands. Samara, Cardigan, pp 301–310

Page SE, Banks C (2007) Tropical peatlands: distribution, extent and carbon storage – uncertainties and knowledge gaps. Peatlands Int 2:26–27

Page SE, Siegert F, Rieley JO, Boehm H-DV, Jaya A, Limin S (2002) The amount of carbon released from peat and forest fires in Indonesia during 1997. Nature 420:61–65

Page SE, Wüst RAJ, Weiss D, Rieley JO, Shotyk W, Limin SH (2004) A record of Late Pleistocene and Holocene carbon accumulation and climate change from an equatorial peat bog (Kalimantan, Indonesia): implications for past, present and future carbon dynamics. J Quatern Sci 19(7):625–635

Page SE, Rieley JO, Wüst R (2006) Lowland tropical peatlands of Southeast Asia. In: Martini IP, Martinez-Cortizas A, Chesworth W (eds) Peatlands: evolution and records of environmental and climate changes, vol 9, Developments in earth surface processes. Elsevier, Amsterdam, pp 145–172

Page SE, Banks CJ, Rieley JO (2007) Tropical peatlands: distribution, extent and carbon storage – uncertainties and knowledge gaps. http://www.geog.le.ac.uk/carbopeat/media/pdf/yogyapapers/p1.pdf

Payne RJ, Blackford JJ (2008) Peat humification and climate change: a multi-site comparison from mires in south-east Alaska. Mires and Peat 3: Art. 9. http://www.mires-and-peat.net/

Pfadenhauer J (1990) Tropische und subtropische Moore. In: Göttlich K (ed) Moor- und Torfkunde. 3. Auflage. E. Schweizerbart'sche Verlagsbuchhandlung (Nägele und Obermiller), Stuttgart, pp 102–113

Polak B (1950) Occurrence and fertility of tropical peat soils in Indonesia. In: Proceedings of the 4th international congress of soil science vol 2, pp 183–185

Rajagopalan G, Sukumar R, Ramesh R, Pant RK, Rajagopalan G (1997) Late Quaternary vegetational and climatic changes from tropical peats in southern India – an extended record up to 40,000 years BP. Curr Sci 73(1):60–63

Rajagopalan G, Ramesh R, Sukumar R (1999) Climatic implications of δ^{13}C and δ^{18}O ratios from C3 and C4 plants growing in a tropical montane habitat in southern India. J Biosci 24(4):491–498

Rieley JO, Page SE (2005) Wise use of tropical peatlands: focus on Southeast Asia. Alterra-Wageningen University and Research Centre and the EU INCO-Strapeat and Restorpeat Partnerships, Wageningen

Rodríguez AR (1999) Conservación de humedales en Venezuela: inventario, diagnóstico ambiental y estrategia. Comité Venezolano de la UICN, Caracas

Rull V (1991) Contribución a la paleoecología de Pantepui y la Gran Sabana (Guayana Venezolana): clima, biogeografía y ecología. Scientia Guaianae 2, CVG-EDELCA, Caracas

Satrio AE, Gandaseca S, Ahmed OH, Ab Majid NM (2009) Effect of precipitation fluctuation on soil carbon storage of a tropical peat swamp forest. Am J Appl Sci 6(8):1484–1488

Schubert C, Fritz P (1985) Radiocarbon ages of peat, Guayana Highlands (Venezuela). Some paleoclimatic implications. Naturwissenschaften 72:427–429

Schubert C, Fritz P, Aravena R (1994) Late Quaternary paleoenvironmental studies in the Gran Sabana (Venezuelan Guayana Shield). Quatern Int 21:81–90

Shier CW (1985) Tropical peat resources – an overview. In: Proceedings symposium tropical peat resources: prospects and potential. International Peat Society, Kingston, pp 29–46

Shimada S, Takahashi H, Haraguchi A, Kaneko M (2001) The carbon content characteristics of tropical peats in Central Kalimantan, Indonesia: estimating their spatial variability in density. Biogeochemistry 53(3):249–267

Sieffermann RG, Fournier M, Triutomo S, Sadelman MT, Semah AM (1988) Velocity of tropical forest peat accumulation in Central Kalimantan Province, Indonesia (Borneo). Proceedings of the 8th international peat congress, Leningrad, pp 90–98

Sjörs H (1980) Peat on earth: multiple use or conservation? Ambio 9:303–308

Stêpniewska Z, Borkowska A, Kotowska U (2006) Phosphorus release from peat soils under flooded conditions of the Leczynsko-Wlodawskie Lake District. Int Agrophysics 20:237–243

Sukumar R, Ramesh R, Pant RK, Rajagopalan G (1993) A δ^{13}C record of late Quaternary climate change from tropical peats in southern India. Nature 364(6439):703–706

Tie YL, Kueh HS (1979) A review of lowland organic soils of Sarawak. Department of Agriculture, Technical Paper 4, Research Branch, Sarawak

Tie YL, Lim CP (1976) Lowland peat soils for sago-growing in Sarawak. In: Tan K (ed) Sago-76. Papers of the 1st international sago symposium, Kuching, pp 187–189

USDA (1999) Soil taxonomy. A basic system of soil classification for making and interpreting soil surveys. Agricultural Handbook 436, 2nd edn. US Department of Agriculture, Natural Resources Conservation Service, Soil Survey Staff. Washington, DC

USDA (2006) Keys to Soil Taxonomy. US Department of Agriculture, Natural Resources Conservation Service, National Cooperative Soil Survey. Washington, DC

Von Post L (1924) Das genetische System der organogenen Bildungen Schwedens. Mémoires sur la nomenclature et la classification des sols. International Committee of Soil Science, Helsinki, pp 287–304

Wheeler R (2003) Forest ecosystems and bogs in arctic, temperate and tropical locations. http://www.uaf.edu/ces/forestry/pdfs/Ecosystems%20and%20Bogs.pdf

White WA, Warne AG, Guevara EH, Aslan A, Tremblay TA, Raney JA (2002) Geo-environments of the northwest Orinoco delta, Venezuela. Interciencia 27(10):521–528

Wikipedia (2008) Peat. http://en.wikipedia.org/wiki/Peat

Wösten JHM, Clymans E, Page SE, Rieley JO, Limin SH (2008) Peat-water interrelationships in a tropical peatland ecosystem in Southeast Asia. Catena 73(2):212–224

Wüst RAJ, Bustin RM, Lavkulich LM (2003) New classification systems for tropical organic-rich deposits based on studies of the Tasek Bera Basin, Malaysia. Catena 53(2):133–163

Yule CM, Gomez LN (2009) Leaf litter decomposition in a tropical peat swamp forest in Peninsular Malaysia. Wetlands Ecol Manage 17:231–241

Zinck JA, García P, Van der Plicht J (2011) Tepui peatlands: age record and environmental changes. In: Zinck JA, Huber O (eds) Peatlands of the Western Guayana Highlands, Venezuela, Chap. 7. Springer, Heidelberg, doi: 10.1007/978-3-642-20138-7_7