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Editors

Peatlands of the Western Guayana Highlands, Venezuela

Properties and Paleogeographic Significance of Peats

Springer

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In Memoriam

We dedicate this book to the memory of Richard Schargel, our mutual friend and contributor to the present volume, who passed away prematurely on March 24, 2011.

Foreword

When one stands somewhere on the Gran Sabana at about 1,400 m above sea level in southern Venezuela and looks around the vast open area, one recognizes the characteristic up to 1,400 m higher rock tables of the Tepuis limiting the horizon. By the sight the naturalist is caught by strong sentimental yearning for being there. He knows that it is an extreme environment up there continuously wet and cool. We already get a touch of it where we stand on the Gran Sabana with its palm swamps, the morichales of *Mauritia flexuosa* of which ALEXANDER VON HUMBOLDT wrote: "*Sie bildet an feuchten Orten herrliche Gruppen von frischem glänzendem Grün, das an das Grün unserer Ellergebüsche erinnert. Durch ihren Schatten erhalten die Bäume die Nässe des Bodens …*" (Alexander von Humboldt 1849). The other face of the medal is that increasing comfort of (eco-) tourism lifts the mystery and provides access to almost everybody, increasingly endangering persistence of this extraordinary natural environment. What we need, of course, is neither yearning nor casual touristic encounter but solid scientific information, knowledge, and understanding. Comprehensive treatment so far does not exist, but this important gap is now filled by this book edited by ZINCK and HUBER.

Peatlands are more dominant in temperate and boreal than in subtropical and tropical zono-biomes of the Earth. The latter only comprise about 10% of all global peatlands. They are peatland ecosystems in tropical tidal flats, river deltas, coastal forest swamps, and flood plains of river basins with moor forests. Simply due to their low abundance they all are very unique. Most unique among all these tropical moor and peatlands are those of the tropical highlands and on top of the Tepuis in Venezuela, the major topic of this book. These peatlands provide the most vivid illustration of the general aspect that life on the Earth is working up the geological surface of the Earth. How life is shaping the geostructural ground to form peat and peatlands is unraveled in the book by interpretation of the chronological record in terms of past environmental changes in geological times. Morphological, physical, and chemical characteristics of the peats and their peculiar soils are described using modern methods of assessment including the use of carbon isotopes with ^{14}C dating of peat deposits and ^{13}C analyses of vegetation history. Coverage of geoecological developments and the structure of extant vegetation provide deep insights into life in these peat landscapes. Studies of physiological ecology of plants of the Tepui peatlands as far as I know are scarce or in fact virtually absent. One conspicuous exception is the pitcher plant genus *Heliamphora* which is endemic to the Tepuis and which comprises carnivorous plants. It has been studied in detail (Jaffe et al. 1992) and received great attention in the literature because as outlined in this book the peats are extremely poor in mineral nutrients especially phosphorus. Carnivory is a means of acquisition of nutrients by plants. The book shows us that other carnivorous plants are abundant in the Tepui peat vegetation, such as species of *Drosera* and *Utricularia*, and there are the species of the tank forming Bromeliaceae genus *Brocchinia* where – especially in *B. reducta* and *B. hechtioides* – we recognize kind of a "protocarnivory", i.e., indications toward evolution of full carnivory (Jolivet and Vasconcellos-Neto 1993). In addition to this subjectively picked example, the reader of the book will find a wealth of other suggestions provoking ecophysiological studies and stimulating further research.

In a changing world with largely unforeseeable global perturbations, the book is an invaluable documentation of an extraordinary natural heritage. The peats of the tropical highlands are a heritage like rainforests and savannas – but much less in the medial limelight – that global ethics should demand to protect and preserve not only because of their uniqueness and natural beauty but – due to farther reaching ecological and environmental implications – also in the very interest of keeping the planet inhabitable for mankind. This is forcefully advocated in this book, which provides a wealth of data, solid knowledge, and sympathetic understanding of the peatlands.

Darmstadt, Germany Ulrich Lüttge
March 2011

References

Alexander von Humboldt (1849) *Mauritia flexuosa* "*at moist places forms magnificent groups of fresh and shiny greenery, which recalls the green of our alder bushes. With their shade these trees maintain the moisture in the soil ...*". Ansichten der Natur. Cotta, Stuttgart

Jaffe K, Michelangeli F, Gonzalez JM, Miras B, Ruiz MC (1992) Carnivory in pitcher plants of the genus *Heliamphora* (Sarraceniaceae). New Phytol 122:733–744

Jolivet P, Vasconcellos-Neto J (1993) Convergence chez les plantes carnivores. Recherche 24:456–458

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Meran, Italy
March 2011

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Chapter 1
Introduction

O. Huber and J.A. Zinck

The neotropical biogeographic region of Guayana lies mostly on the ancient Guayana Shield (or "Guiana Shield") in the northeast of South America, covering an area of approximately 2.5 million km^2. This large region extends from the shores of the Atlantic Ocean in the east (50°W) to the foothills of the Colombian Andes in the west (73°W), and from the lower Orinoco river in Venezuela in the north (8°N) to the lower Amazon river in Brazil in the south (3°S). It includes parts of Venezuela, Colombia, and Brazil, and the full extent of the three Guianas (i.e., Guyana, the former British Guiana; Suriname, the former Dutch Guiana; and the French Guiana or Guyane) (Fig. 1.1). This remote land, often called the "Lost World" after the title of a novel written by British author Conan Doyle (1912), is emplaced on one of the oldest continental nuclei of the western hemisphere, the Archean "Amazon craton" formed around 3,500 million years (3.5 Ga) ago.

The biogeographic Guayana region in Venezuela shows a variety of landscapes from sea level in the Orinoco river delta up to the summits of the Guayana Highlands, which are the second highest mountain massif in the Neotropics after the Andes. The densely forested lowland plains and peneplains are home to numerous indigenous groups among which the Yanomami and Ye'kwana Amerindians are best known. The intermediate uplands are formed by two large plateaus showing several planation surfaces: the Gran Sabana region, located in the southeast of the Bolívar state, and the extensive mid-elevation mountain range of Sierra Parima that forms the eastern boundary of the Amazonas state. More than 50 impressive table-mountains jut up from the forested lowlands and undulating savanna-covered uplands to form the Guayana Highlands. These mostly flat-topped mesetas, called "tepuis" by some local Indian groups, extend mainly between 2,000 and 2,500 m a.s.l. The highest elevations are Cerro de la Neblina (or Pico da Neblina), located near the Equator along the southernmost Brazilian–Venezuelan border, with 3,014 m a.s.l. (Brewer-Carías 1988), and Mts. Roraima and Marahuaka that reach elevations of about 2,800 m a.s.l.

Tepui mesetas harbor unique life forms and outstanding biological treasures. Spatially isolated since remote times from the surrounding biota by steep rocky walls of up to 1,000 m elevation, the high-mountain ecosystems of the Guayana

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Fig. 1.1 Location of the Venezuelan Guayana (*bold contour line*), the biogeographic Guayana region (*hatched line*), and the underlying geologic Guayana Shield (*dotted line*) (modified from Huber and Foster 2003)

Highlands represent perhaps the only truly pristine environments still existing on earth. It was hardly 125 years ago that scientific exploration of the tepui summits started, yielding since then an astonishing amount of plants and animals never seen before elsewhere. Many of these unique plants and animals, biogeographically included in the term "Pantepui biota," are growing and living on thick, black, extremely acid, water-saturated organic soils that form high-mountain peatlands. Peat bogs lie directly atop the rocky surface of the table-mountains, which in most cases consists of quartz sandstone and, to a lesser degree, granitic and gneissic rocks.

The first paleoecological research on tepui peats was carried out scarcely 25 years ago in the eastern Guayana Highlands, Bolívar state (Schubert and Fritz 1985; Briceño and Schubert 1990; Briceño et al. 1990; Rull 1991; Huber 1992; Schubert et al. 1994). Following these pioneer studies, three multidisciplinary field missions including paleoecological research groups took place between 1991 and 1996 in the central and western parts of the Venezuelan Guayana Highlands, Amazonas state: the first (November 1991 and March 1992) to the tepuis Duida, Marahuaka and Huachamakari in the Duida-Marahuaka National Park; the second (February 1993) to the Cuao-Sipapo massif including Cerro Autana; and the third (March 1996) to the northern section of Sierra de Maigualida. One major objective of all three missions was the biophysical characterization of the tepui-summit environment. The present publication focusing on tepui peatlands is a product of these field missions.

For dealing with tropical highland landscapes, the subject of this book relates partly to two earlier volumes of Ecological Studies. Volume 146 on *Inselbergs:*

Biotic Diversity of Isolated Rock Outcrops in Tropical and Temperate Regions (edited by Porembski and Barthlott 2000) describes the variety of plant communities and vegetation types that develop on granitic and gneissic domes. Individual tepui mesetas could be etymologically assimilated to inselbergs (from German Insel = island and Berg = mountain) as they appear in the landscape in the form of rocky table-shaped islands overhanging the surrounding lowlands. Although inselberg and tepui bear some similarity in the sense that both are partly to largely devoid of vegetation cover, the concept of inselberg is usually restricted to dome-like reliefs developed on igneous–metamorphic rocks in the lowlands, while tepuis are assemblages of mesetas, rather than isolated relief units, constituted by siliceous sedimentary rocks and circumscribed by high vertical walls reaching the highlands. Igneous–metamorphic mountain massifs are much more extensive in the western Guayana Highlands than siliceous sedimentary plateaus, but bare inselberg-type rock outcrops are less frequent than rocky mesetas. Therefore, peatlands are mainly found on the large, flat to slightly concave tepui summits, while they are less common and less extensive on the narrow, convex dome-backbones. This is the reason why our work concentrates on tepui peats and secondarily refers to peats developed on igneous–metamorphic mountains. The second volume bearing some relationship with our study topic is volume 198 on *Gradients in a Tropical Mountain Ecosystem of Ecuador* (edited by Beck et al. 2008). The tepui landscape with vertical cliffs several hundreds meter high offers limited possibilities for vegetation gradients to develop, although vertical vegetation shifts caused by past climate changes are still matter of debate. By contrast, vegetation gradients with elevation from lowlands to uplands to highlands are characteristic of the igneous–metamorphic massifs. Thus our study is to a given extent complementary to these two former volumes.

The book is composed of nine chapters covering a variety of features including geology, geomorphology, vegetation, and soils that characterize the biophysical environment of tepui summits in the western Guayana Highlands, southern Venezuela. The core subject concentrates on the properties, age record, and paleogeographic significance of the peats that have deposited during the Holocene in (pseudo-)karstic depressions on siliceous sedimentary and igneous–metamorphic rocks. As tropical peatlands, especially tropical highland peats, are much less known than temperate and boreal peats, the book starts providing in Chap. 2 an overview on tropical and subtropical peats. Chapter 3 gives a description of the biophysical environment of the Guayana region as a whole, with emphasis on geology, climate, and vegetation, and then zooms into the highland study areas focusing on the vegetation cover and the floristic composition of the formations found atop the tepuis and specifically on peatlands. Types of vegetation cover, hydrologic regime, and organic materials make the tepui peatlands a very special ecosystem. However, what really distinguishes tepui and dome peatlands from others is their geomorphic setting, as peat formation and development are intimately related to specific (pseudo-)karstic landscape features that are described in Chap. 4. The physical and chemical characterization of organic soils in general and peats in particular requires the application of special laboratory techniques and procedures. These are described in Chap. 5, highlighting the ad hoc adaptations that were needed to carry out the determinations. Using laboratory and field data, the morphological, physical, and chemical properties of the peats are described, analyzed, and interpreted in Chap. 6, followed by a discussion on the taxonomic classification of the peat materials. The following Chap. 7 deals with the description of the peat sampling sites, the carbon-14 dating of selected peat layers, and the interpretation of the peat age record with respect to peat formation and environmental changes during the Holocene. The peat age record of the western Guayana Highlands documented here is unique, as no new data collection has taken place in these areas since our exploration missions in the early 1990s. Chapter 8 is an extra-regional contribution focusing on the origin of organic matter that leads to peat formation based on data from the southeastern Guayana Highlands. A synthesis compiled from the relevant conclusions of the individual contributions is presented in Chap. 9. The book closes with an Appendix which provides the field description of profiles and sites and the corresponding laboratory data. Included are also some mineral soils that are usually associated with the organic soils on the tepui summits as well as some typical lowland soils that are derived from the weathering of the tepui rocks.

References

Beck E, Bendix J, Kottke I, Makeschin F, Mosandl R (eds) (2008) Gradients in a tropical mountain ecosystem of Ecuador, vol 198, Ecological Studies, Springer, Berlin

Brewer-Carías C (ed) (1988) Cerro de la Neblina: resultados de la expedición 1983–1987. FUDECI, Caracas

Briceño H, Schubert C (1990) Geomorphology of the Gran Sabana, Guayana Shield, southeastern Venezuela. Geomorphology 3:125–141

Briceño H, Schubert C, Paolini J (1990) Table-mountain geology and surficial geochemistry: Chimantá Massif, Venezuelan Guayana Shield. J S Am Earth Sci 3(4):179–194

Doyle AC (1912) The lost world. Hodder & Stoughton, New York

Huber O (ed) (1992) El macizo del Chimantá, Escudo de Guayana, Venezuela. Un ensayo ecológico tepuyano. Oscar Todtmann Editores, Caracas

Huber O, Foster M (eds) (2003) Conservation priorities for the Guayana Shield: 2002 consensus. Conservation International – CABS, Guiana Shield Initiative, UNDP, IUCN, Washington DC

Porembski S, Barthlott W (eds) (2000) Inselbergs: biotic diversity of isolated rock outcrops in tropical and temperate regions, vol 146, Ecological Studies. Springer, Berlin

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

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

Chapter 2
Tropical and Subtropical Peats: An Overview

J.A. Zinck

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),