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New classification systems for tropical organic-rich deposits based on studies of the Tasek Bera Basin, Malaysia

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Abstract

Most schemes in common use for field and laboratory classification of peats were developed in boreal and humid temperate regions and do not recognize the distinctive features and specific uses of tropical peats, such as those of the Tasek Bera Basin in tropical Peninsular Malaysia. The important aspects of peat texture (morphology of constituents and their arrangement) and laboratory ash content (residue after ignition) need modification to be valuable for classifying these and other tropical peat deposits. In the Tasek Bera Basin, most of the deposits would not be considered as peat according to some classification schemes, even though most have C contents >25%. We propose a new three-group (fibric, hemic, sapric) field texture classification applicable to tropical organic deposits, which is similar to the system of the US Soil Taxonomy. The classification is based on the following factors: (1) visual examination of the morphology of the peat constituents (texture); and (2) estimates of fiber content and matrix (finest fraction of peat consisting of highly humified organic matter and inorganic material). The classification is applicable to all organic deposits with < 65% ash (i.e., >35% loss on ignition). We also present a new laboratory classification of organic soils based on ash and C content. The US Soil Taxonomy classifies organic soils as having more than 12–18% organic C, depending on clay content. Ash content and these limits for organic soils allow the discrimination of four main groups: peat, muck, organic-rich soil/sediment and mineral soil/sediment. Peat is defined as having an ash content of 0–55%, muck 55–65%, organic-rich soil/sediment 65–80% and mineral soil/sediment 80–100%. The peat class is further subdivided into

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very low ash (0–5%), low ash (5–15%), medium ash (15–25%), high ash (25–40%) and very high ash (40–55%) subclasses.
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1. Introduction

Andriesse (1988) defined tropical peats as all organic soils deposited in mires of the tropics and subtropics lying between latitudes 35°N and 35°S, including those at high altitudes. Although tropical peatlands are widespread, there have been few attempts to classify tropical peats (e.g., Andriesse, 1988; Esterle, 1990; Paramananthan, 1998). The composition and texture of tropical peats differ markedly from humid temperate peat deposits (e.g., Polak, 1933; Yonebayashi et al., 1992). Most tropical mires, as in Southeast Asia, occur under tropical rain forests, with trees such as Dipterocarpaceae, Euphorbiaceae, Guttiferae, Leguminosae, Myrtaceae, Ulmaceae, etc. (e.g., Polak, 1933; Anderson, 1983) and few bryophytic peats occur. Despite major differences in ecological regime, structure, texture and composition between temperate and tropical deposits, peat classifications developed in humid temperate regions are commonly used for tropical peat deposits.

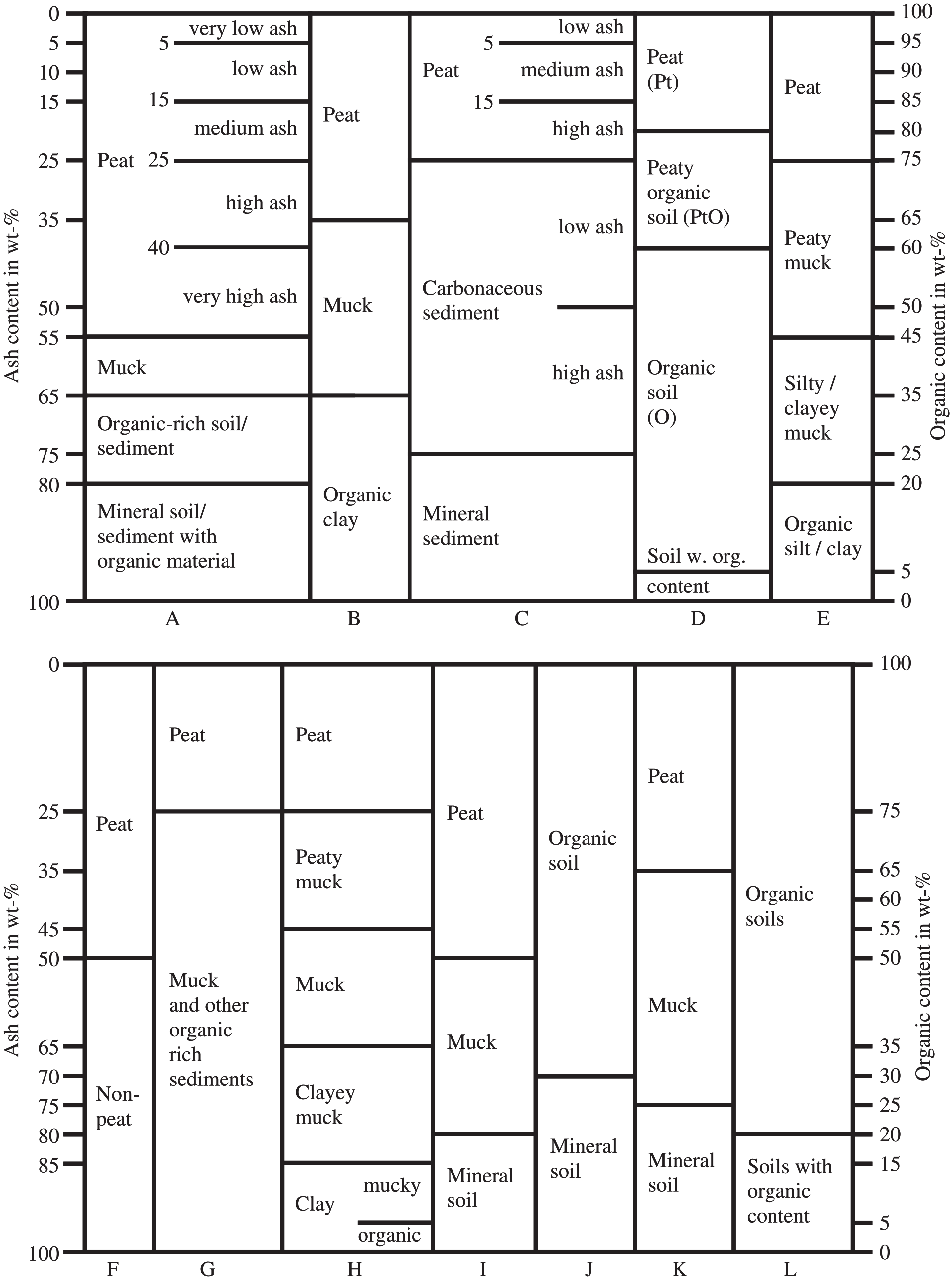
In a study of the Tasek Bera Basin, Peninsular Malaysia, we found that existing peat classification schemes failed to characterize adequately the tropical deposits of this lowland area, where extensive, thin to thick (7 m) peat and organic-rich deposits occur. Various classification systems were applied and frequently utilized field and laboratory techniques were tested on the Tasek Bera deposits. The results provide the basis for a new field and laboratory classification system for tropical organic deposits.

Field descriptions of organic soils should include structure, texture, degree of decomposition, pH and botanical constituents, because these allow peatlands to be evaluated for environmental, geological, geotechnical, agricultural, horticultural or energy purposes (Schneekloth, 1977; Kivinen, 1980). Field classification is critical because during sample transportation and storage there may be changes in texture, degree of humification, colour, density, porosity and chemical properties such as pH and Eh.

One problem of classifying organic soils in the field is the definition of organic soils. The agricultural systems of Canada (CSSC, 1987), USA (Soil Survey Staff, 1990) and Malaysia (Paramananthan, 1998) require a minimum thickness of organic

Notes to table 1:
(A) Proposed classification of this study, (B) the Moris classification (Moris, 1989), (C) the classification of the Organic Sediments Research Center of the University of South Carolina (Andrejko et al., 1983), (D) the system of the American Society for Testing and Materials (Landva et al., 1983), (E) the Jarrett system (Jarrett, 1983), (F) the Russian classification (Mankinen and Gelfer, 1982), (G) the previous classification of the American Society for Testing and Materials (ASTM, 1982), (H) the Louisiana Geological Survey system (Kearns et al., 1982), (I) the classification of the International Peat Society (Kivinen, 1968), (J) the Canadian System of Soil Classification (CSSC, 1987), (K) the Davis classification (Davis, 1946) and (L) the Arman system (Arman, 1923).

Table 1
Various classification systems of peat and organic soils based on ash and organic content



material (40–120 cm) for a soil to qualify as organic. The Canadian system requires also >17% organic C (>30% LOI), and the US Soil Taxonomy and the Malaysian systems require at least 12–18% organic C (>35% LOI), depending on the clay content.

The CSSC (1987) includes in the order "Organic" four Great Groups: Fibrisol, Mesisol, Humisol and Folisol. Fibrisols are soils of relatively undecomposed fibric organic matter (H1–H4 on the scale of von Post, 1924), Mesisols are intermediate between Fibrisols and Humisols, and Humisols are at the most advanced stage of decomposition (H7–H10 on the von Post scale) with few recognizable fibers. Folisols are soils composed of upland organic material (forest origin) and >40 cm thick.

The US Soil Taxonomy (Soil Survey Staff, 1990) uses the term Histosol for organic soil material; which has four sub-orders: Fibrists, Hemists, Saprists and Folists. The dominant soil material (sapric, hemic or fibric) of the subsurface tier (60–120 cm) is used to differentiate the first three Sub-orders and Folists are soils that are not saturated with water for more than a few days per year.

The Malaysian Soil classification (Paramananthan, 1998) has three sub-orders in the Order Organah: Gunorgs, Daunorgs and Gamborgs. Gunorgs are montane peats with an isothermic or cooler temperature regime. Daunorgs are litter peats, which have an O horizon mainly derived from leaf litter, twigs and branches resting on parent material. Gamborgs are lowlands peats with an aquic moisture regime. The thickness of the organic deposits (Ombro >150 cm and Topo 50–150 cm) is used at the Great Soil Group level and the dominant organic soil material in the subsurface tier (50–100 cm) is used to define the sub-groups, i.e., saprik, hemik or fibrik (e.g., Fibrik Ombrogamborg).

The International Peat Society (IPS) classifies peat based on a combination of botanical composition (moss, sedge, wood), degree of decomposition (weakly, medium, strongly) and trophic status (oligotrophic = nutrient-poor, mesotrophic, eutrophic = nutrient-rich) (Kivinen, 1980).

One of the main problems of these classification systems is that they are based on a control section of limited thickness, which often differs greatly in composition and/or degree of humification from underlying organic materials. For tropical peats, which are often several meters thick, a description of all layers of the organic deposits is more important than classifying the deposit according to a single, often shallow, control section.

Many methods have been proposed for classifying peat in the laboratory (e.g., Jackson, 1958; Andrejko et al., 1983; Riley, 1989). These provide valuable information on peat as a fuel or horticultural product, or for land management (e.g., lime or nutrient requirement, drainage depth, construction stability, etc.). Some chemical and physical analyses, such as ash and fiber content, allow the subdivision and precise characterization of organic sediments and soils. The ash content is important for peats utilized as fuel (fuel < 25% ash) and Andrejko et al. (1983) among others regard ash content as the most important factor for classifying peat deposits (Table 1).

The purpose of this study was to select the most useful existing peat classification system and adapt it for tropical organic deposits. The new scheme is intended for use at an interdisciplinary level, i.e., geologists, soil scientists, agriculturalists, etc.

2. Properties used to classify peat deposits

In 1930, the Second International Congress of Soil Science defined peat as an organic soil at least 50 cm thick, 1 ha in aerial extent and containing < 35% ash (Tie, 1982). Organic soils with 35–65% mineral matter were called "muck" and mineral soils were those with < 35% organic matter. Other properties used to characterize organic soils and differentiate peat types and behaviour include texture, degree of humification, fiber content, pH and colour. Texture is defined as the morphology and arrangement of the organic and inorganic particles of the peat (Forsaith, 1916), although MacFarlane and Radforth (1968) referred to this property as structure. Texture is important for peat characterization in the field and is usually determined by measuring the degree of humification of the organic matter, which depends on vegetation type and mire morphology. With increasing humification, polymers such as fulvic and humic acids are formed, which influence soil acidity, nutrient availability and cation exchange capacity. Also, with increasing decomposition bulk density increases, free water decreases, the plant-water slurry becomes darker and plant material decays into smaller fragments, i.e., the matrix content increases.

The degree of humification of organic matter is commonly measured in the field using the 10-point scale (H1–H10) of von Post (1924) that describes the consistency and colour of the peat-water slurry of a rubbed sample (Table 2). The von Post system also determines the root/wood fiber content (R0, V0 = roots and wood absent, R4, V4 = completely fibrous peat with no matrix) and moisture content (B1 = air-dry to B5 = water saturated humified peat). Several authors have adapted and/or modified the von Post system (Landva et al., 1983; Bell, 1992). Dachnowski (1924), working on North American peat deposits, developed a system that classified peat based on topographic position and botanical constituents. Radforth (1955) expanded the classification of von Post (1924) and Dachnowski (1924) to 16 categories (categories 1–7 = amorphous–granular, 8–11 = fine–fibrous, 12–16 =coarse–fibrous). The system is based on the morphology of botanical components and takes no account of particle size, orientation, texture or chemical constitution. MacFarlane (1969) subsequently extended this system. The US Soil Taxonomy (Soil Survey Staff, 1990) utilizes for agricultural purposes a three-stage classification first introduced by Farnham and Finney (1965): fibric, hemic and sapric peat (Table 2), based on fiber content and size. This classification was later applied to tropical ombrogenous peat deposits in Sarawak, Malaysia, by Esterle (1990) (Table 2) and was found to be the most practical classification scheme of peat texture during our field campaign.

Moisture content is determined in the laboratory from the "oven-dry" and "as-received" weights. Organic soils generally have much greater moisture contents than non-organic soils; they often exceed 100% (oven-dry weight) and can reach 3000% (Farnham and Finney, 1965).

The ash content is obtained by ignition (dry ash) or chemical oxidation (wet ash). Temperatures from 50 to 750 °C have been used for dry ashing (e.g., Andrejko et al., 1983; Riley, 1989) and hydrogen peroxide (H_2O_2) or sodium hypochlorite (NaOCl) for wet ashing (Jackson, 1958). The ash of peat depends on vegetation type, bedrock composition and hydrology (i.e., geomorphology of the peat deposits, climate) and consists fundamentally of three components: (a) a biogenic component (often autochthonous plant material,

Table 2
Comparison of classification schemes based on the degree of humification for peat deposits according to the system of von Post (1924), the US Soil Taxonomy system (Soil Survey Staff, 1990), the Esterle system (Esterle, 1990) and the new proposed system (see Table 6 for details)

Von Post (1924)	US Soil Tax.		Esterle (1990)		this study
H1 Completely undecomposed peat, releases clear water. Plant remains easily identifiable. No amorphous material. H2 Almost completely undecomposed peat, releases clear or yellowish water. Plant remains still easily identifiable. No amorphous material. H3 Very slightly decomposed peat, releases muddy brown water but no peat passes between the fingers. Plant remains still identifiable and no amorphous material.	FIBRIC Mostly *Sphagnum* High fiber content	**Peat, organic soil material containing less than 25 wt-% ash**	**Fibric** Reddish-brown peat with >66% fibres; long slender roots and rootlets with diameters 1-10 mm embedded in fibrous or granular matrix from which clear water can be extracted.	**Peat, muck, organic soil material containing less than 65 wt-% ash**	**Fibric**
H4 Slightly decomposed peat, releases very brown muddy water. No peat passes between the fingers but the plant remains are slightly pasty and have lost some of the identifiable features. H5 Moderately decomposed peat, releases very muddy water with small amounts of amorphous granular peat escaping between the fingers. The residue is strongly pasty. H6 Moderately strongly decomposed peat with a very indistinct plant structure. When squeezed, about 1/3 of the peat passes between the fingers. The residue is strongly pasty but shows the plant structure more distinctly than before squeezing.	HEMIC Mostly reed-sedge Moderate fiber content		**Coarse hemic** hemic peat with long, slender roots and rootlets. **Hemic** Reddish-brown peat with 33-66% fibres; short or equant fragments of roots and rootlets, bark and leaf fragments generally less than 1cm embedded in granular matrix from which clear to murky water can be extracted.		**Hemic**
H7 Strongly decomposed peat with a lot of amorphous material and faintly recognizable plant structures. When squeezed, about 1/2 of the peat escapes between the fingers. The water is very dark and almost pasty.	SAPRIC Low fiber content Often high ash		**Fine hemic** fine grained hemic peat with sapric matrix, partially extrudes through fingers.		
H8 Very strongly decomposed peat with a large quantity of amorphous material and very dry indistinct plant structure. When squeezed, about 2/3 of the peat escapes between the fingers. A small quantity of pasty water may be released. The plant material remaining in the hand consists of residues such as roots and fibres that resist decomposition. H9 Practically fully decomposed peat with hardly any recognizable plant structure. When squeezed, almost all peat escapes between the fingers as uniform paste. H10 Completely decomposed peat with no discernible plant structure. When squeezed, all the wet peat escapes between the fingers.			**Sapric** Dark brown to black, with <33% fibres; fine granular material with the consistency of paste from which water can not be extruded and deforms as paste upon squeezing.		**Sapric**

less commonly allochthonous); (b) a terrigenous component (allochthonous mineral matter from windblown dust and/or flooding); and (c) an orthochemical component (in situ precipitated minerals). The biogenic components include phytoliths, which are common in endodermal and ectodermal tissues of many wetland plants, and minerals (silica and carbonate) secreted by charophytes, ostracods, sponges and diatoms (Miller, 1918; Cohen, 1974; Hodson and Evans, 1995). Orthochemical components show little or no evidence of transportation and include carbonates, sulphates and minerals formed under reducing conditions, such as pyrite. High sulfur peat deposits (>1% S) often contain authigenic pyrite and result from syn- or post-depositional marine influences (Casagrande et al., 1977; Phillips and Bustin, 1996). Peat classification systems based on ash content do not differentiate between biogenically derived (phytoliths, sponge spicules, diatoms) and inorganic terrigenous or detrital matter. As a consequence, peat samples with similar ash contents may contain very different amounts of detrital mineral matter and have different physical, chemical and geotechnical properties.

The carbon, nitrogen and sulfur (CNS) contents of peat deposits are the most valuable properties for fuel (energy grade) and agricultural uses. Carbon content is also used for environmental assessments, such as how much C a drained peatland could release to the atmosphere. It can also provide information about the type of organic material and the stage of decomposition (Andriesse, 1988). Nitrogen content indicates the trophic or nutrient status for plant growth and microbial activity. C/N ratios are used to determine the degree of humification and the amount of N available to plants and microbes (Brady and Weil, 1996). Sulfur content is important when utilizing peat as fuel because sulfur dioxide is produced during combustion.

3. The Tasek Bera (Malaysia) peatland

The Tasek Bera wetland system was chosen as an example of a tropical peat deposit to evaluate different classification systems. It is a lowland mire system with various floral habitats and thus includes a variety of peat deposits. The setting results in autochthonous and allochthonous peat deposits derived from trees, shrubs and sedges. The area is therefore ideal for testing the applicability of peat classification systems for lowland tropical peats.

3.1. Physiography

The Tasek Bera wetland is located in the central part of Peninsular Malaysia, in the east-central State of Pahang and northeastern Negeri Sembilan (Fig. 1). Local peat accumulation in the basin began some 6000 years ago and progressive terrestrialization of several lakes and paludification of the riparian area has led to extensive peat deposits over an area of about 60 km^2 (Wüst and Bustin, 1999). The peat deposits have a complex internal structure because of shifting vegetation over the last few thousand years. They are dominated by monocotyledons, often with a low matrix component that results from persistent high water levels during much of the year. However, the forest swamp peat commonly has a high granular, amorphous matrix and abundant large woody fragments.

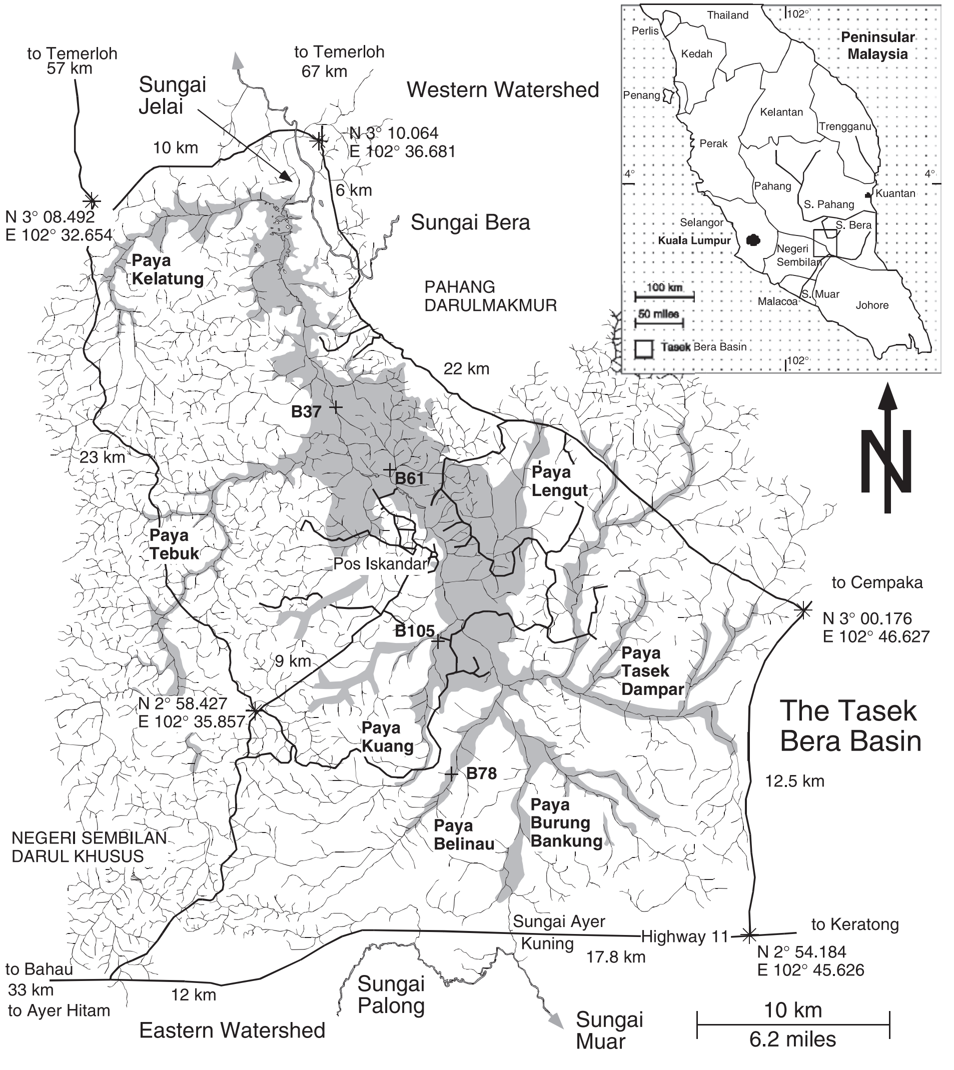


Fig. 1. Location of the Tasek Bera peat basin in Peninsular Malaysia (inset map). The map shows roads (black solid line), tributaries, wetland distribution (shaded area) and core sites (Bxx) of the present study.

The area is divided into lowland dipterocarp rain forest, low-ash minerotrophic peat swamp forest, high-ash minerotrophic peat swamp forest, *Pandanus helicopus* shrubs, *Lepironia articulata* sedges and open water areas (Wüst and Bustin, 1999).

3.2. Sample sites, sample collection and field analyses

Samples from 137 cores were collected along continuous traverses across and along the Tasek Bera Basin at 150–200 m intervals using a Macaulay peat sampler. The Macaulay sampler allows collection of 5-cm diameter uncompressed cores in 50-cm increments from the top to the base of the peat. Four representative cores of the area are described in detail in this paper. Cores B61 and B37 were collected in open *Lepironia* and *Pandanus* environments in the northern and central parts of the basin (Fig. 1). Cores B105 and B78 were collected in the peat swamp forest environment of the central and southern basin. All organic deposits are underlain by thick (>50 cm) fluviatile or lacustrine quartz-rich clay and silt sediments. Each core was described in the field according to the classification schemes of von Post (1924), Esterle (1990), Paramananthan (1998), Moris (1989) and the modified Esterle system that we propose as a new field classification scheme. The samples were wrapped in aluminium foil and placed into split PVC pipes (50 cm long) for transportation. Soil pH was measured with a Cardy® Model C-1 digital pH meter using 1:1 soil/distilled water (Sumner, 1994). Maximum instrumental deviation from the pH 7 and 4 standards was 0.12 pH units. Soil Munsell colour was measured for all cores, because colour has been utilized to classify peat and muck in the past (Dawson, 1956).

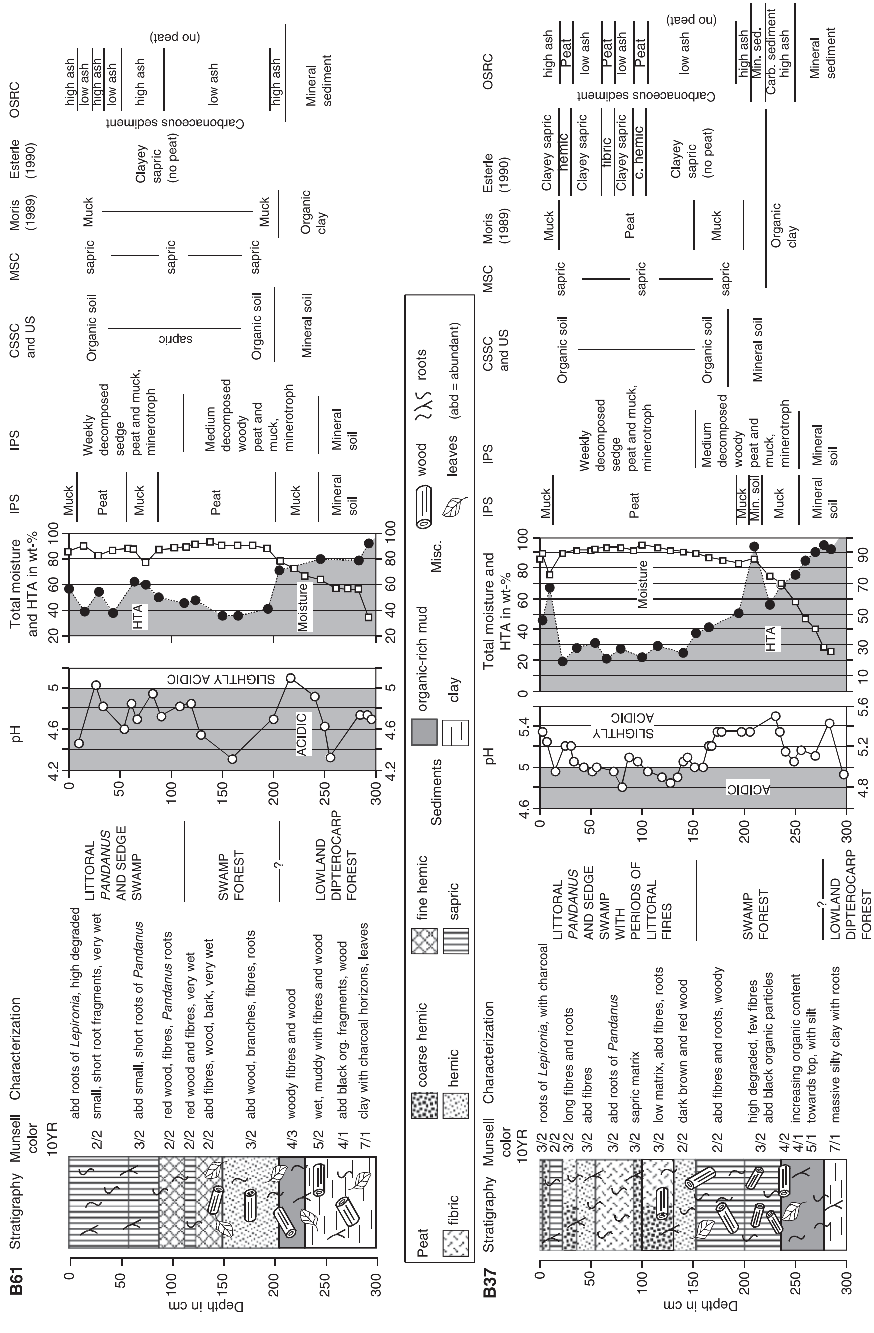
3.3. Laboratory analysis

Moisture and ash contents were determined according to ASTM standard procedures (Jarrett, 1983). Samples were oven-dried at 85–105 °C or freeze-dried for 7 days for determination of moisture content. Ash content and loss on ignition (LOI) were determined by igniting the oven-dried sample in a muffle furnace at 750 °C for at least 2 h (ASTM-D 2979; Jarrett, 1983). Because several temperatures have been used in the past for ash analysis of peat deposits (e.g., Andrejko et al., 1983; Riley, 1989), we also compared the most commonly utilized temperatures to test accuracy and completeness of combustion. Duplicate samples were burnt at 375 °C for 24 h, 440 °C for 16 h, 550 °C for 4–8 h and 750 °C for 2 h. The ash is expressed as a percentage of the mass of the oven-dried or freeze-dried sample. Total C, N and S of 132 samples from 20 cores were determined with a Carlo Erba NA-1500 analyzer (Verardo et al., 1990). Total C is equal to total organic C as a result of the slightly acid to acid environment of Tasek Bera.

4. Results

4.1. Littoral *Pandanus* and *Lepironia* environments (cores B61 and B37)

Core B61 (Fig. 2) was collected in the open *Pandanus* and *Lepironia* environment of the central littoral area, north of Pos Iskandar (Fig. 1). The peat is 206 cm thick and underlain by organic-rich mud (25 cm) and dark gray and white clay (Munsell colour 10YR 5/2 to 7/1) with abundant roots, wood and charcoal fragments. The units between 100 and 300 cm depth have abundant tree fragments, such as wood, bark, leaves, roots, branches and charcoal. The top 100 cm are dominated by *Pandanus* and *Lepironia* roots and fragments. The fine hemic and sapric peat units are mostly very dark brown (10YR 2/2). The hemic peat is very dark grayish brown (10YR 3/2) and the organic-rich mud is brown (10YR 4/3). The clay shows a gradual downward colour change from grayish brown to light gray (10YR 5/2 to 7/1). The pH ranges between 4.2 and 5.2. The organic



B61
Depth in cm
Stratigraphy
Munsell color 10YR
Characterization
abd roots of Lepironia, high degraded
2/2 small, short root fragments, very wet
3/2 abd small, short roots of Pandanus
2/2 red wood, fibres, Pandanus roots
2/2 red wood and fibres, very wet
2/2 abd fibres, wood, bark, very wet
3/2 abd wood, branches, fibres, roots
4/3 woody fibres and wood
5/2 wet, muddy with fibres and wood
4/1 abd black org. fragments, wood
7/1 clay with charcoal horizons, leaves
LITTORAL PANDANUS AND SEDGE SWAMP
SWAMP FOREST
?
LOWLAND DIPTEROCARP FOREST
pH
SLIGHTLY ACIDIC
ACIDIC
Total moisture and HTA in wt-%
HTA
Moisture
IPS
Muck
Peat
Muck
Peat
Muck
Mineral soil
Weekly decomposed sedge peat and muck, minerotroph
Medium decomposed woody peat and muck, minerotroph
Mineral soil
CSSC and US
Organic soil
sapric
Organic soil
Mineral soil
MSC
sapric
sapric
sapric
Moris (1989)
Muck
Muck
Organic clay
Esterle (1990)
Clayey sapric (no peat)
OSRC
high ash
low ash
high ash
low ash
high ash
low ash
(no peat)
Carbonaceous sediment
high ash
Mineral sediment
Peat
fibric
coarse hemic
hemic
fine hemic
sapric
Sediments
organic-rich mud
clay
Misc.
wood
leaves
roots
(abd = abundant)
B37
Depth in cm
Stratigraphy
Munsell color 10YR
Characterization
3/2 roots of Lepironia, with charcoal
2/2
3/2 long fibres and roots
3/2 abd fibres
3/2 abd roots of Pandanus
3/2 sapric matrix
3/2 low matrix, abd fibres, roots
2/2 dark brown and red wood
2/2 abd fibres and roots, woody
3/2 high degraded, few fibres abd black organic particles
4/2 increasing organic content
4/1 towards top, with silt
5/1
7/1 massive silty clay with roots
LITTORAL PANDANUS AND SEDGE SWAMP WITH PERIODS OF LITTORAL FIRES
SWAMP FOREST
?
LOWLAND DIPTEROCARP FOREST
pH
SLIGHTLY ACIDIC
ACIDIC
Total moisture and HTA in wt-%
Moisture
HTA
IPS
Muck
Peat
Muck
Min. soil
Muck
Mineral soil
Weekly decomposed sedge peat and muck, minerotroph
Medium decomposed woody peat and muck, minerotroph
Mineral soil
CSSC and US
Organic soil
Organic soil
Mineral soil
MSC
sapric
sapric
sapric
Moris (1989)
Muck
Peat
Muck
Organic clay
Esterle (1990)
Clayey sapric
hemic
Clayey sapric
fibric
Clayey sapric
c. hemic
Clayey sapric (no peat)
OSRC
high ash
Peat
low ash
Peat
low ash
Peat
low ash
(no peat)
Carbonaceous sediment
high ash
Min. sed.
Carb. sediment
high ash
Mineral sediment

deposits have 35–60% ash. Total moisture content ranges from 82% to 92%. The deposits are classified as weakly to medium decomposed, minerotrophic sedge and woody peat and muck (Kivinen, 1968), organic deposits (Sub-order Saprist) (CSSC, 1987; Soil Survey Staff, 1990), saprik Ombrogamborg (Paramananthan, 1998), muck (Moris, 1989), clayey sapric (Esterle, 1990), or low- to high-ash carbonaceous sediments (Andrejko et al., 1983).

Core B37 (Fig. 2) was collected in the open *Lepironia* and *Pandanus* environment of the central littoral Tasek Bera Basin (Fig. 1). Silty fluvial white clay (10YR 7/1) with organic fragments below 278 cm depth is overlain by organic-rich mud (236–278 cm) with some woody fragments and peat (0–236 cm). The uppermost deposits (0–131 cm) contain abundant *Pandanus* and *Lepironia* roots, stem fragments and fibers. The lowermost, highly degraded units (131–236 cm) have abundant wood fragments. All peat units are very dark brown and very dark grayish brown (10YR 2/2, 3/2). The organic-rich mud has a gradational colour change from dark grayish brown to grayish brown (10YR 4/2 to 5/1) and the silty clay is light gray (10YR 7/1). pH varies between 4.8 and 5.5. Total moisture of the peat is 85–96%. Ash content varies between 10% and 58%. Sulfur content is fairly constant (0.3–0.5%) throughout the upper profile (0–177 cm) and decreases in the organic-rich mud (0.2%) to as little as 0.07% in the clay (Table 3). N content is greater in the top part of the profile (1.1–1.3%) and decreases in the mud and clay to 0.05%. C content ranges between 0.3% and 40%. It increases from 20% at the top to 41% at a depth of 75 cm (Table 3) and is least in the basal mud and clay (15% and 0.3%, respectively). The deposits are classified as weakly decomposed, minerotrophic sedge peat overlying medium decomposed woody peat and muck (Kivinen, 1968), organic soil (Sub-order Fibrist) (CSSC, 1987; Soil Survey Staff, 1990), fibrik Ombrogamborg (Paramananthan, 1998), peat and muck (Moris, 1989), clayey sapric (no peat) with some hemic, coarse hemic and fibric peat layers interbedded (Esterle, 1990), or mainly low-ash carbonaceous sediments with interbedded high ash carbonaceous sediment and peat layers (Andrejko et al., 1983).

4.2. Peat forest environments (cores B105 and B78)

Core B105 (Fig. 3) was collected in the Paya Kuang, south of Pos Iskandar (Fig. 1). White clay (351–400 cm) is overlain by organic-rich clay (313–351 cm) and strongly decomposed woody peat (0–313 cm). The uppermost 200 cm are very dark brown (10YR 2/2). The bottom peat units are dark brown, dark grayish brown and very dark grayish brown (10YR 3/3, 4/2, 3/2). The organic-rich mud and clay are dark grayish brown, grayish brown and light gray (10YR 4/2, 5/2, 7/1). pH increases slightly from the top (4.4) to the bottom of the profile (5.25). Total moisture of the peat ranges from 87% to 92%. The

Fig. 2. (Top) Core B61 from *Lepironia* and *Pandanus* environment. Core description, chemical and physical characteristics and classification according to the International Peat Society (IPS) (Kivinen, 1968), the Canadian System of Soil classification (CSSC, 1987), the US Soil Taxonomy (Soil Survey Staff, 1990), the Malaysia Soil classification (MSC) (Paramananthan, 1998), the (Moris, 1989) system, the Esterle classification (Esterle, 1990) and the classification of the Organic Sediments Research Center (OSRC) of the University of South Carolina (Andrejko et al., 1983). HTA = high temperature ash; abd = abundant. (Bottom) Core B37 from *Lepironia* and *Pandanus* environment. Core description, chemical and physical characteristics and classification according to IPS, CSSC, US Soil Taxonomy, MSC, Moris, Esterle and OSRC.

Table 3
Ash, C, N and S contents of 132 samples (20 cores) from the Tasek Bera Basin (Wüst, 2001). Figures in italic are data for the cores described in this study (Figs. 2–4)

Core	Depth in cm	Description	Ash wt.%	N total wt.%	C total wt.%	S total wt.%	C/N
B37	*6*	*hemic*	*49.86*	*1.22*	*19.43*	*0.28*	*15.95*
B37	*34*	*hemic*	*32.27*	*1.34*	*28.64*	*0.47*	*21.34*
B37	*75*	*fibric*	*10.41*	*1.22*	*40.91*	*0.39*	*33.61*
B37	*113*	*hemic*	*23.95*	*1.32*	*34.29*	*0.37*	*26.03*
B37	*150*	*hemic*	*17.74*	*1.05*	*36.77*	*0.32*	*35.00*
B37	*177*	*sapric*	*38.20*	*1.32*	*26.23*	*0.38*	*19.87*
B37	*224*	*sapric/mud*	*94.33*	*0.77*	*14.69*	*0.17*	*19.09*
B37	*285*	*clay*	*94.73*	*0.05*	*0.27*	*0.07*	*5.38*
B38	0	sapric/mud	68.79	0.94	12.57	0.19	13.41
B38	14	sapric/silt/sand	76.56	0.59	7.47	0.12	12.70
B38	29	sapric/silt/sand	75.80	0.60	9.83	0.14	16.38
B38	50	hemic	72.53	0.88	15.41	0.18	17.44
B38	75	sapric/clay	76.23	0.55	8.67	0.12	15.76
B38	136	sapric/clay	77.75	0.73	9.79	0.16	13.47
B38	215	sapric/clay	62.86	0.73	9.43	0.16	12.83
B38	300	mud	76.30	0.73	12.89	0.23	17.74
B38	375	clay	83.57	0.33	5.80	0.09	17.85
B38	417	clay	92.00	0.23	3.83	0.05	16.67
B49	25	hemic	39.78	1.26	24.87	0.28	19.71
B49	41	sapric	46.64	1.21	22.79	0.23	18.79
B49	72	sapric	40.39	1.26	25.52	0.32	20.25
B49	130	sapric	47.85	1.05	22.49	0.26	21.37
B49	167	sapric	44.92	0.99	23.93	0.19	24.22
B49	204	sapric	42.14	1.19	27.42	0.22	23.04
B49	252	sapric	53.83	0.85	20.77	0.17	24.53
B68	8	sapric	47.02	1.15	23.38	0.32	20.26
B68	25	sapric	49.42	1.29	22.91	0.40	17.72
B68	39	hemic	27.89	1.49	32.78	0.45	22.06
B68	74	sapric	32.43	1.73	29.94	0.37	17.27
B68	99	hemic	46.61	1.14	22.09	0.29	19.34
B68	135	hemic	32.05	0.79	28.87	0.47	36.59
B77	34	sapric	23.62	1.84	33.29	0.29	18.06
B77	66	hemic	20.50	1.99	34.19	0.23	17.14
B77	91	hemic	25.91	1.89	33.20	0.18	17.59
B77	156	hemic/sand	44.57	1.38	25.11	0.14	18.16
B78	*62*	*sapric*	*8.56*	*1.83*	*48.53*	*0.18*	*26.55*
B78	*170*	*sapric*	*2.71*	*1.62*	*53.13*	*0.21*	*32.80*
B78	*280*	*sapric*	*3.92*	*1.27*	*53.59*	*0.33*	*42.26*
B78	*375*	*sapric*	*5.46*	*1.23*	*52.41*	*0.24*	*42.47*
B78	*480*	*sapric*	*10.96*	*1.08*	*50.85*	*0.44*	*47.04*
B89	0	sapric	43.27	1.46	28.41	0.19	19.50
B89	10	sapric	38.31	1.22	32.53	0.21	26.71
B89	18	sapric	38.31	1.33	38.11	0.14	28.65
B89	30	sapric	12.35	1.49	49.58	0.33	33.33
B89	56	sapric	14.19	1.51	49.26	0.27	32.57
B89	90	sapric	33.33	1.13	35.14	0.27	31.21
B89	135	sapric	20.67	1.06	44.83	0.24	42.45
B89	158	sapric	32.44	0.79	36.72	0.16	46.24
B89	160	mud	31.27	0.75	37.44	0.31	49.98

Table 3 (*continued*)

Core	Depth in cm	Description	Ash wt.%	N total wt.%	C total wt.%	S total wt.%	C/N
B89	189	clay	41.36	0.64	29.79	0.40	46.61
B98	32	sapric	47.58	1.24	22.15	0.19	17.82
B98	43	mud	66.85	0.75	11.62	0.13	15.45
B98	52	mud	66.17	0.78	12.23	0.12	15.63
B98	85	mud	59.43	0.76	15.37	0.13	20.18
B98	91	mud	60.12	0.81	15.72	0.19	19.42
B98	115	hemic	44.75	0.93	21.94	0.19	23.55
B98	136	mud	62.72	0.54	14.22	0.09	26.52
B142	3	mud	69.81	0.71	9.95	0.16	13.96
B142	22	hemic/mud	57.32	0.89	14.36	0.19	16.17
B142	61	hemic	34.20	1.36	28.98	0.39	21.27
B142	71	hemic	27.90	1.31	32.94	0.44	25.07
B142	91	hemic	25.53	1.27	34.64	0.40	27.19
B142	143	hemic	36.50	1.27	26.94	0.38	21.21
B142	191	hemic	28.76	1.19	32.48	0.43	27.35
B142	271	sapric	37.54	1.01	27.41	0.36	27.16
B144	5	sapric/mud	49.98	1.29	22.40	0.32	17.35
B144	22	sapric	53.06	1.28	18.84	0.32	14.70
B144	45	hemic	37.86	1.19	25.95	0.31	21.73
B144	61	hemic	36.05	1.59	26.69	0.42	16.81
B144	82	hemic	39.15	1.51	25.38	0.45	16.76
B144	111	hemic	32.13	1.45	29.63	0.40	20.47
B144	141	sapric	26.58	1.34	33.17	0.50	24.78
B144	175	sapric	51.01	1.22	19.38	0.31	15.92
B144	193	sapric	45.13	1.13	23.60	0.33	20.84
B144	231	sapric	38.94	1.06	28.38	0.29	26.72
B144	275	organic rich mud	45.00	0.72	23.78	0.31	33.13
B6	25	coarse hemic	26.37	1.38	34.52		25.05
B6	67	fibric	28.67	1.25	32.40		25.96
B6	125	fibric	42.87	1.25	26.60		21.27
B6	170	fibric	34.17	1.37	29.54		21.55
B6	210	fibric	42.47	1.09	24.38		22.29
B6	240	hemic/mud	58.67	0.79	15.24		19.35
B20	32	sapric	41.58	1.30	22.76		17.46
B20	60	coarse hemic	26.13	1.20	33.87		28.33
B20	104	hemic	32.42	1.54	28.51		18.50
B20	155	hemic	34.60	1.20	31.07		25.95
B20	215	sapric	51.20	0.90	18.65		20.71
B20	275	sapric	51.82	0.76	20.40		26.72
B25	25	sapric	45.84	1.41	23.37		16.63
B25	70	coarse hemic	36.98	1.36	25.92		19.02
B25	115	sapric	40.85	1.28	25.94		20.25
B25	195	fine hemic	16.02	1.08	38.33		35.36
B25	265	fine hemic/mud	66.63	0.58	11.10		19.19
B25	330	organic rich clay	78.92	0.32	5.81		18.36
B53	26	sapric/mud	52.68	1.25	21.06		16.88
B53	112	sapric	39.27	1.24	26.24		21.10
B53	178	fine hemic	39.85	0.83	25.99		31.16
B53	233	organic rich mud	72.51	0.38	8.59		22.57

(continued on next page)

Table 3 (*continued*)

Core	Depth in cm	Description	Ash wt.%	N total wt.%	C total wt.%	S total wt.%	C/N
B53	340	hemic/mud	52.14	0.52	19.02		36.36
B53	412	fibric/mud	58.74	0.41	16.34		39.53
B53	484	organic rich mud	81.25	0.20	4.29		21.94
B59	27	organic rich mud	66.80	0.74	11.54		15.60
B59	75	hemic/mud	62.93	0.68	12.68		18.58
B59	135	fine hemic/mud	60.18	0.87	14.24		16.39
B59	170	fine hemic/mud	62.46	0.62	12.20		19.56
B59	200	coarse hemic/mud	44.37	0.88	24.97		28.43
B64	28	fine hemic	62.75	0.98	13.34		13.59
B64	75	sapric	55.00	1.08	17.35		16.07
B64	115	sapric	41.95	1.36	24.88		18.23
B64	160	coarse hemic	34.40	0.87	28.87		33.11
B64	190	sapric	39.90	0.90	26.43		29.49
B64	215	hemic	31.11	0.83	30.00		35.98
B87	35	sapric	5.52	1.55	44.53		28.70
B87	75	hemic	3.09	1.48	45.81		30.96
B87	145	hemic	1.67	1.29	45.37		35.18
B87	215	sapric	3.57	1.44	46.00		31.93
B87	305	sapric	3.20	1.30	46.53		35.77
B87	395	sapric	25.07	0.72	37.58		52.43
B87	425	sapric/mud	24.21	0.68	38.52		56.39
B105	*35*	*fine hemic*	*22.28*	*2.08*	*33.60*		*16.14*
B105	*90*	*sapric*	*13.43*	*1.27*	*38.87*		*30.71*
B105	*140*	*sapric*	*22.58*	*1.49*	*33.89*		*22.73*
B105	*195*	*sapric*	*20.57*	*1.56*	*34.99*		*22.41*
B105	*245*	*sapric*	*24.47*	*1.38*	*33.33*		*24.23*
B105	*305*	*sapric/mud*	*43.31*	*0.87*	*26.50*		*30.34*
B106	20	sapric	28.67	1.83	30.91		16.85
B106	85	sapric	13.64	1.41	38.18		27.07
B106	145	sapric	17.62	1.62	36.14		22.33
B106	195	sapric	28.09	1.46	29.92		20.48
B106	255	sapric/mud	54.18	0.52	18.31		34.94
B106	310	organic rich mud	44.82	0.67	23.10		34.27
B115	25	fine hemic	46.27	1.36	22.58		16.58
B115	48	sapric	30.94	1.35	30.32		22.39
B115	95	sapric	28.07	1.19	35.84		30.13
B115	165	fine hemic	46.02	1.17	23.02		19.60
B115	240	sapric	26.74	0.83	32.20		38.77
B115	350	organic rich mud	74.94	0.30	7.72		26.10

ash content is 6–24% in the top 230 cm and 27–54% in the underlying peat units (230–310 cm). N content decreases from 2.1% (35 cm) to 0.9% (305 cm) (Table 3). C content ranges between 26% and 39% throughout the profile. The C/N ratio is least at the top (16) and increases downwards to 30. The profile is classified as medium decomposed, minerotrophic woody peat and basal muck (Kivinen, 1968), Haplosaprist (Soil Survey Staff, 1990), Saprik Ombrogamborg (Paramananthan, 1998), peat and basal muck (Moris, 1989), fine hemic and sapric peat overlying clayey sapric deposits (Esterle, 1990), or medium to high ash peat overlying carbonaceous sediments (Andrejko et al., 1983).

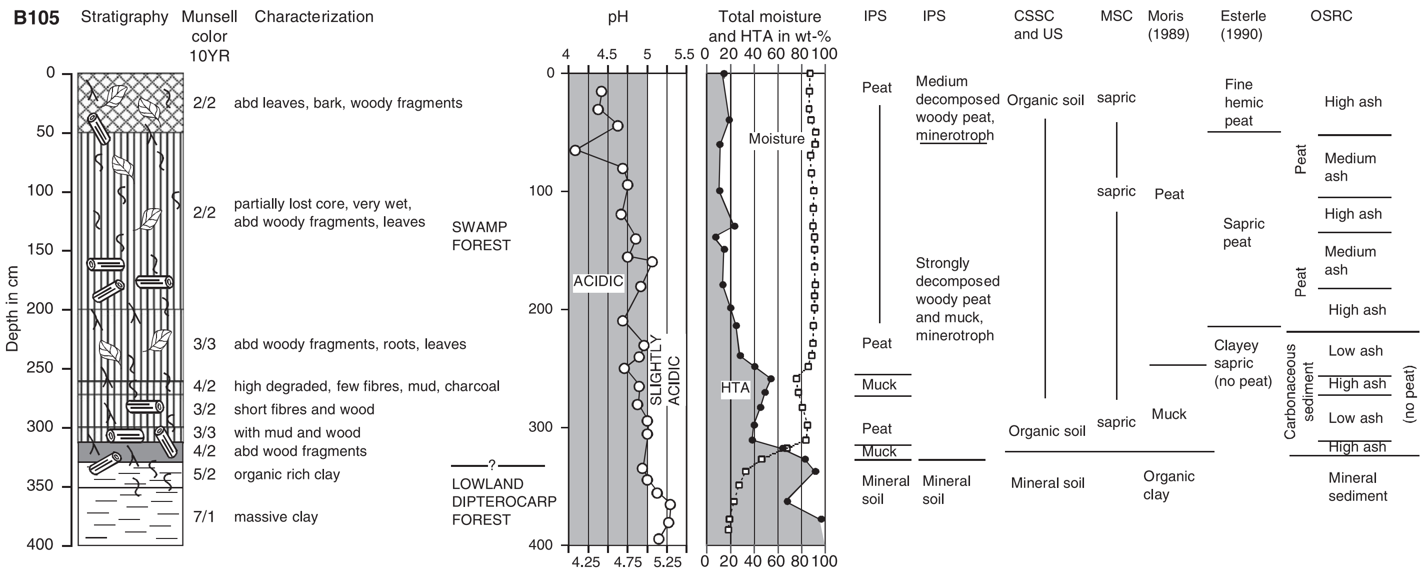


Fig. 3. Core B105 from swamp forest environment. Core description and chemical and physical characteristics. Classification according to IPS, CSSC, US Soil Taxonomy, MSC, Moris, Esterle and OSRC. See Fig. 2 for legend.

Core B78 (Fig. 4) from the Paya Belinau area in the southern Tasek Bera Basin (Fig. 1) has highly decomposed woody, sapric peat overlying black organic-rich mud (500–559 cm) and white clay (559–600 cm). The lowermost peat deposits contain abundant hard wood remains (logs, stems and branches). Fine hemic peat occurs at 250–269, 137–150 and 31–74 cm, hemic peat at 330–345 and 74–90 cm and fibric peat at 90–100 cm. Modern hardwood roots were found to a depth of 2 m. The water table was at a depth of 20 cm. The uppermost fine hemic, hemic and fibric units are very dark brown (10YR 2/2), the underlying peat dark reddish brown (5YR 2.5/2 and 5YR 3/4) and the mud and clay very dark brown and black. The black clay overlies a white (10YR 7/1) kaolinitic clay. The pH of core B78 was 3.3–3.7. Total moisture content ranged between 85% and 93%. Ash contents are very low (2–12%) in the uppermost 400 cm, but greater (9–31%) between 400 and 500 cm depth. S content increases slightly from 0.2% at the top (62 cm) to 0.5% at the bottom (480 cm) (Table 3), and N decreases from 1.8% to 1.1%. The C content is high throughout the profile (49–54%). The C/N ratio increases from top to basal peat from 26 to 47. The deposits are classified as medium to strongly decomposed, ombrotrophic woody peat and basal muck (Kivinen, 1968), organic soil (Sub-order Hemist) (CSSC, 1987; Soil Survey Staff, 1990), Hemik Ombrogamborg (Paramananthan, 1998), peat and basal muck (Moris, 1989), coarse hemic, hemic, fine hemic and sapric peat overlying clayey sapric deposits (Esterle, 1990), or low to medium peat overlying carbonaceous sediments (Andrejko et al., 1983).

4.3. Moisture

Moisture as-received values for the Tasek Bera peats were in general >400% with some samples having values up to 1900% (Fig. 5). In the acrotelm and lower parts of the profiles, it was often 400–800% and greatest (800–1700%) in the middle parts of the peats. The organic-rich mud had moisture as-received contents between 50% and 400% and the underclay between 20% and 100%. Some samples may have had slightly decreased moisture values because of loss of pore water during transportation and storage.

4.4. Ash

The ash contents of all samples ranged from 1% to 98% (Table 3, Fig. 6). A characteristic trend of upward decreasing ash contents with one or more higher values towards the top occurs in most cores from the sedge area (e.g., Fig. 2). The topsoil is often enriched in ash content (55–60%). Most of the organic-rich deposits in the cores (Table 3, Figs. 2–4) are classified from these results as muck or organic clay (Moris, 1989), as carbonaceous shale and mineral sediment (Andrejko et al., 1983), or as high ash peat, muck and organic-rich soil in the classification suggested in this study (Table 1). The ash content of the peat deposits in the southern swamp forest of Paya Belinau (e.g., core B78) is very small and loss on ignition often exceeds 95% (Fig. 4). The ash of this peat is almost all biogenic. Tests on modern wetland plants have shown that tropical plants incorporate up to 10% inorganic material (Table 4), which contributes to the total ash content of organic soils/sediments.

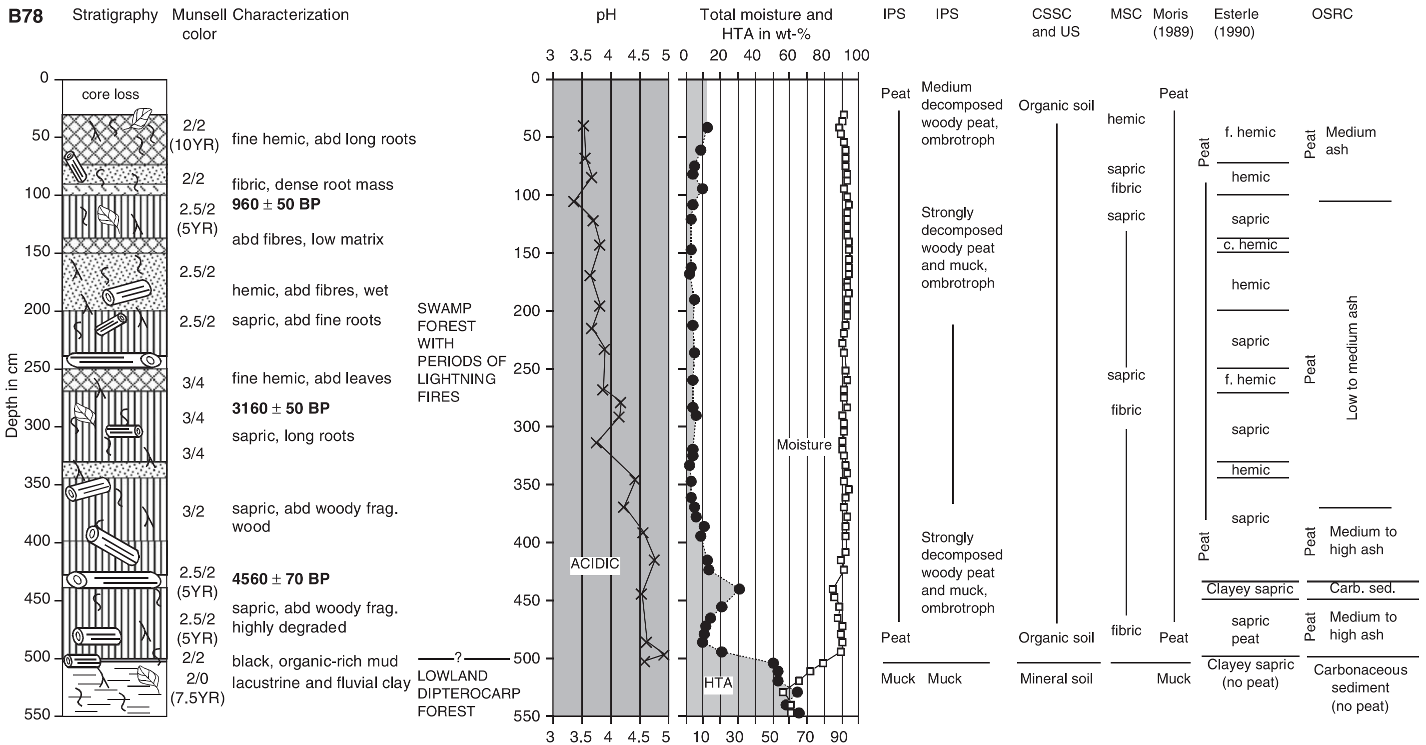


Fig. 4. Core B78 from swamp forest environment. Core description and chemical and physical characteristics. Classification according to IPS, CSSC, US Soil Taxonomy, MSC, Moris, Esterle and OSRC. US Soil Taxonomy classifies the deposits as Haplohemists and the Malaysian Soil Taxonomy as Hemik Ombrogambists, riverine-clayey dysic, autochthonous, low ash, woody. See Fig. 2 for legend.

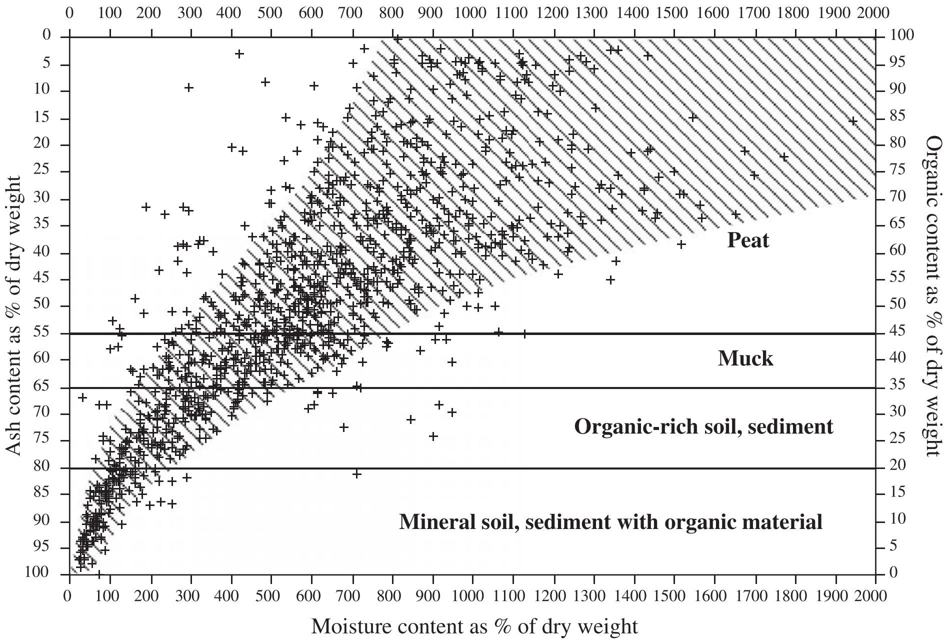


Fig. 5. Moisture as-received versus ash content for samples from the Tasek Bera Basin (>2000 samples from 148 cores). The shaded area represents the range of moisture content of tropical organic soils based on this study. The different classes shown are those proposed for our new classification scheme of tropical organic soils (peat, muck, organic-rich soil, mineral soil).

The standard furnace temperature and time for ash determination have been widely debated. Tests on Canadian peats with different degrees of humification showed that there were only small changes in ash contents between 500 and 900 °C or between 1 and 4 h (Riley, 1989, p. 26). Jarrett (1983) concluded that a temperature of 550 °C for approximately 16 h should be used for ash analysis because ashing below 500 °C is slow. Other comparisons of peat samples burnt at different temperatures showed negligible variations in ash contents between 375 and 750 °C (Andrejko et al., 1983), but major differences between 50 and 375 °C, probably because of incomplete combustion of organic matter (Table 5). In peats with >20% ash, maximum deviations between low and high temperature ashing results were 25% and in samples with < 10% ash the difference was up to 48%. Most of our own samples were ashed at 750 °C for 2 h, but the tests at different temperatures showed that ignition at 375 °C for 24 h would be sufficient (Table 5).

Temperatures above 440 °C can lead to partial dehydration and/or volatilization of some mineral contents; for example, pyrite (FeS_2), a common authigenic mineral in peat and coal, is transformed to pyrrhotite (FeS) or ferric oxides at >500 °C (ASTM, 1982; Taylor et al., 1998). Higher temperatures (e.g., >550 °C) also increase the loss of hydroxyl groups from calcium sulfates and clay minerals and loss of carbon dioxide from carbonates. If gypsum is present, bassanite may form above 60 °C (Moore and Reynolds, 1997) and thus wet ashing methods (e.g., Jackson, 1958) are recommended if subsequent

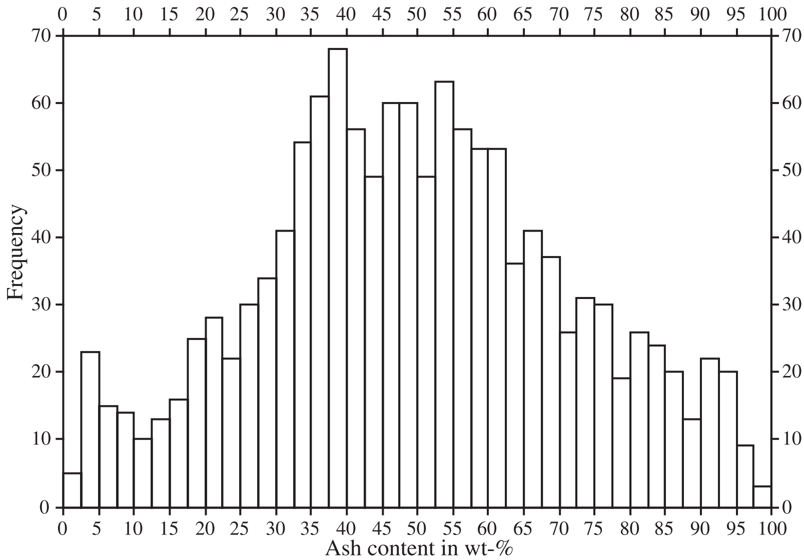


Fig. 6. Histogram of ash contents (>2000 samples from 148 cores) of peats from the Tasek Bera Basin (Wüst, 2001). The distribution over the whole spectrum (0–100%) makes the Tasek Bera deposits suitable for peat classification purposes.

analysis of mineral matter is required. Unless mineralogical analyses of the ash are required, we therefore recommend high temperature ashing at 375 °C for 24 h or 750 °C for 2 h, though both can slightly underestimate ash content through decomposition of clay and other minerals.

4.5. Organic carbon, nitrogen and sulfur

The C content of all samples ranged from 0.27% to 53.6%, the N content from 0.05% to 2.1% and the S content from 0.05% to 0.5% (Table 3). The S values are typical of those for freshwater peat deposits (e.g., Neuzil and Cecil, 1994). The low N contents indicate that

Table 4
Ash content (percent dry-weight) of plants from the Tasek Bera mire system

Plant species	Plant part	Ash content (wt.%)
Pandanus helicopus	leaf	5.6
	stem	3.1
	thick roots	2.9
	micorrhizoms	5.3
Lepironia articulata	seeds	2.0
	leaf tip	8.2
	stalk	4.1
	roots	7.5
Eleocharis spp.	stalk	9.1

Table 5
Comparison of ashing results for peat and organic soil samples ignited at different temperatures from around the world (Andrejko et al., 1983) and the Tasek Bera Basin (Wüst, 2001)

Location	Core	Depth (cm)	LTA, 50–150 °C	HTA, 375 °C	HTA, 550 °C	HTA, 750 °C
Finland			7.07	4.05	3.85	4.01
Quebec (Canada)			2.18	1.92	1.86	1.79
Maine (USA)			71.94	56.03	57.37	60.32
Minnesota (USA)			29.22	21.67	20.61	20.82
North Carolina (USA)			14.72	10.46	9.89	9.16
South Carolina (USA)			8.3	5.16	4.63	4.28
South Carolina (USA)			5.94	4.81	4.8	4.59
Georgia (USA)			6.18	na	4.86	4.79
Florida (USA)			23.31	23.38	17.73	13.09
Tasek Bera (MY)	B37	86	na	25.21	24.12	23.94
Tasek Bera (MY)	B61	187	na	45.77	44.45	44.23
Tasek Bera (MY)	B141	95	na	57.60	56.43	56.16
Tasek Bera (MY)	B103	315	na	59.50	58.30	58.06
Tasek Bera (MY)	B105	106	na	12.38	11.50	11.18
Tasek Bera (MY)	B78	143	na	3.73	3.37	3.33

The differences between low temperature (50–150 °C) (LTA) and high temperature (375–750 °C) (HTA) ashing methods can be as large as 50%, but differences between 375 and 750 °C are often small (na = not available).

nutrients for present plant growth are very limited and the peat deposits are meso- to oligotrophic (Taylor et al., 1998). The central and southern forest peats (e.g., B105 Fig. 3; B78, Fig. 4) have much greater C contents than the northern sedge peat profiles (e.g., B37, Fig. 2). The C/N ratio ranges between 12 and 56 (Table 3). In both reed and forest environments, the C/N ratio of the acrotelm is about 15. In the catotelm of the peat profiles (50–500 cm depth), it ranges from 15 to 56. In general, there is little correlation between depth and sulfur content. N and C contents tend to increase with depth. Some cores show a slight increase of the C/N ratio with increasing depth.

4.6. Degree of humification

The often-used 10-point scale of von Post (1924) (Table 2) and the 16-category scale of Radforth (1955) for quantifying humification in the field were found to be impractical in the Tasek Bera area. Three problems were encountered.

(1) Differences between individual stages were subtle and required field experience to differentiate them. Tests for the H1–10 stages utilizing the pyrophosphate colour index (PCI) (Stanek and Silc, 1977) showed no difference between von Post classes 5 and 10 and little between classes 2 and 4. Tie (1990) reported similar problems for Malaysian peat samples utilizing the fiber after rubbing test, which showed large differences between classes 1 and 5, but small differences between classes 5 and 10.

(2) During the El Niño event in 1997, some topsoil deposits were dry and no water to determine the degree of humification could be extracted. It is common for the water content to decrease during the intermonsoon period in tropical peatlands, so that determination of colour of the extractant liquid is difficult or impossible.

(3) Tropical forest peat deposits, such as those of SE Asia, are often composed of densely interwoven woody material, dominated by roots with trunks, stumps, branches, leaves and fruits (seeds) of trees and understory shrubs in a dark brown to black amorphous, gelatinous matrix. The woody constituents are coarse and resistant to rubbing so that the peat is classified as fibric or hemic independent of the amount of amorphous material. In some coarse fibric peats, the fine amorphous matrix may be lost during sampling under water-saturated conditions. In addition, many tropical Holocene peats, including those in the Tasek Bera Basin, have greater wood contents in the subsurface than in the uppermost catotelm and acrotelm layers (Polak, 1933; Coulter, 1950; Andriesse, 1974; Anderson, 1983; Esterle, 1990; Phillips, 1995; Neuzil, 1997). In the Tasek Bera Basin, the fragments of sedges and pandan break down more easily than woody fragments, so that most of the deposits are defined as lowland sapric organic soils, e.g., Haplosaprists (Soil Survey Staff, 1990) or Saprik Ombro- or Topogamborg (Paramananthan, 1998). Such deposits are common on river-banks and in open water areas in Southeast Asia.

The three-group scale of Esterle (1990), adopted from the US Soil Taxonomy, allows easy classification of tropical organic deposits, but differentiates only soils with $<25\%$ ash; all other deposits with organic matter >25% ash are clayey sapric. Therefore, it is only applicable to ombrogenous (low ash) peat deposits and excludes the widespread minerotrophic, lowland deposits of the tropics. It was developed for fuel and energy purposes where peat was defined by analogy with coal as containing $<25\%$ ash. However, our field investigations in Tasek Bera have shown that it is impossible visually to distinguish peats with $<25\%$ ash from organic deposits with >25% ash, or even between those with 20% and 35% ash, mainly because mineral matter occurs partly in plant fragments such as roots and wood (Table 4). Earlier studies revealed the same problem (Waksman and Tenney, 1928; Farnham and Finney, 1965). Our field investigations grouped together all organic deposits with up to 65% ash, because of the difficulty of estimating ash content in the field.

5. Discussion and proposed classification schemes

Existing field and laboratory methods used for temperate and boreal peat deposits in Europe and North America failed to fully characterize and classify the tropical organic deposits of Tasek Bera for the following reasons:

(1) Temperate and boreal peats are often dominated by bryophytes and shrubs. Root penetration is thus shallow and decomposition rates are often low. In contrast, tropical peatlands have various tree species (e.g., Polak, 1975; Anderson, 1983), with roots penetrating the organic deposits for as much as several meters. Rates of biomass production and primary decomposition are high. Subsurface input of organic matter from decaying roots and root exudates is therefore much greater in tropical than in temperate peat deposits. Hence, the rubbing test and examination of liquid extracted from tropical peat led to incorrect characterization of texture, which is often fibric because of woody components.

(2) Existing classification schemes for temperate and boreal peats are based on selected characteristics for specific uses in the fields of agriculture, engineering, energy, etc., rather

than having a generic approach. This results in a lack of correlation between field observations and laboratory test results, because field investigations are often regarded as less important than laboratory results, and also limits the interpretation of data collected in the field.

(3) Classifications of organic soil for agricultural purposes (e.g., CSSC, 1987; Soil Survey Staff, 1990; Paramananthan, 1998) are based on a control section. Hence, a 5-m-thick peat deposit would be classified according to the upper 50-cm section of the profile, ignoring the nature and origin of the underlying deposit. A full description and characterization of the complete stratigraphic section is required for classification.

5.1. Problems with existing peat classification schemes based on ash and C content

Comparison of various classification systems based on ash content (Table 1) reveals the problem of laboratory-based schemes. Many were designed for particular interests (e.g., fuel utilization) and less to distinguish between different types of organic deposits. ASTM (D 2607-69, discontinued 09/28/90 with no replacement; Kearns and Davison, 1983 and Andrejko et al., 1983) defined peat as having < 25% ash. The ash classification system of the OSRC (Andrejko et al., 1983) classifies most "peat" at Tasek Bera as carbonaceous sediment. Two problems with the OSRC classification system are: (1) the ash content of peat is limited to < 25% (see also Esterle, 1990); and (2) it uses the term "sediment" for peat samples with >25% ash, i.e., most autochthonous organic deposits of Tasek Bera would therefore be classified as sediments.

The rationale for the 25% ash content for peat comes from the coal industry. Good quality coal is defined as having < 25% ash (Taylor et al., 1998) and the ash content of good metallurgical coals is limited to a maximum of 10% (Bustin et al., 1983). A maximum of 25% ash (23% in Russia) was also proposed for peat to be utilized as fuel in northern temperate regions (Mankinen and Gelfer, 1982). In the tropics, the peat used as fuel usually has < 7% ash (Andriesse, 1988).

Despite these ash limits of 7–25%, many peat scientists have described organic soils in the field as "peat", though they had ash contents much greater than 25%. Waksman and Tenney (1928) described peat from Florida (saw-grass, lake) and New Jersey (lowmoor) with ash contents between 10% and 60%, Farnham and Finney (1965) described sapric peats with 26–66% ash contents, Bell (1978) described peats from Sheffield (Blacket Bog), UK, with ash contents as high as 45% and Andrejko et al. (1983) included as "peat" a sample from Maine with 20% C and 63% ash. The long list of organic deposits with >25% ash described as "peat" support our field observations from the Tasek Bera Basin that differentiating peats with 20% or 40% ash contents in the field is indeed difficult or impossible.

The CSSC and the US Soil Taxonomy define organic soils as having at least 12% organic C. All the Tasek Bera deposits with up to 65% ash (45–100% LOI) meet that requirement. In tropical peat deposits, C contents are often between 40% and 60% (e.g., Andriesse, 1988; Moris, 1989; Phillips, 1995; Neuzil, 1997). Tie (1990) reported values between 35% and 44% from Malaysia. In the peat of the Tasek Bera Basin, C ranges from 20% to 54%. According to the system of Moris (1989) (Table 1), most of the organic deposits in the Tasek Bera Basin are classified as peat (0–35% ash) and muck (35–65% ash).

Table 6
Proposed field classification system of peat texture for tropical humic deposits based on the Esterle (1990) classification

PEAT AND MUCK Ash content <65 wt-%	Fibric	Very dark grayish brown to dark brown fibrous peat with long, weakly decomposed organic fragments and fibers such as roots, leaves, twigs, branches, and bark. Low matrix component. On squeezing, clear to slightly murky water extrudes the peat.	No to very little amorphous matrix, very coarse fibers and long, slender roots	*Coarse fibric*	Fc
			Coarse to fine fibers and roots	*Fibric*	F
	66% fibers				
	Hemic	Very dark gray to very dark brown peat with abundant fiber particles, roots and wood fragments embedded in anamorphous, granular matrix (sapric). Murky to brown gelatinous water escapes through fingers.	Very coarse roots and fibers, often low amorphous matrix	*Coarse hemic*	Hc
			Coarse to fine fibers and roots	*Hemic*	H
			Very short roots and fiber particles with few long organic fibres, high sapric matrix component	*Fine hemic*	Hf
	33% fibers				
	Sapric	Dark brown to very dark brown or black peat with fine, particulate organic matter with short roots, fibers. Sometimes long and large woody fragments, roots. Abundant dark brown to black amorphous, granular matrix. Upon squeezing, gelatinous, dark brown to black paste extrudes through the fingers. Plant structure of some fragments discernible. Sapric peat often changes color upon air exposure (oxidizing).	Abundant coarse plant fragments	*Sapric with abundant wood, roots, fibers*	Sw
			Coarse to fine fibers and roots	*Sapric*	S
			High amorphous matrix, almost no plant fragments discernible	*Sapric with few short roots, fibers, wood*	Ss
			Sapric peat with little sand (often quartz), silt or clay particles. Sticky matrix upon squeezing	*Sapric with mud (often muck)*	Sm
Organic-rich soils and sediments Ash >65 wt-%	Organic-rich mud	Dark gray, dark grayish brown to gray hemic, or sapric (rarely fibric) "peat" with a high mineral matter content. Matrix consists of amorphous granular, humic compounds with mainly fine silt and clay size mineral matter. A smeary paste escapes upon squeezing. Often long and coarse organic fibers and roots.	Abundant woody fibers, roots, plant fragments	*Organic-rich mud with abundant fibers, roots, wood*	Mow
			Few discernible tree fragments (roots, wood, leaves, charcoal)	*Organic-rich mud with few fibers, small roots*	Moo

Both peat and muck deposits (soils with <65% ash contents) are divided into fibric, hemic or sapric deposits. Materials with >65% ash are described as organic-rich mud or sediments.

5.2. Proposed textural classification of peat

We propose a textural classification system for tropical peat soils based mainly on field examination, as suggested by Esterle (1990), because of the high plant diversity in tropical peatlands and the resulting problematic rubbing results. The key factor of this classification, which has three groups (fibric, hemic and sapric), is visual assessment of the percentages of fiber and matrix components. Both peat (ash content of 0–55%) and muck (ash 55–65%) are included in this, because it is difficult to separate them in the field. We also propose key abbreviations for use with the classification. Once the deposits are classified into one of the three groups, further subdivision is often possible. Laboratory analysis is required to differentiate between low-ash, medium-ash and high-ash peat or muck and is discussed later.

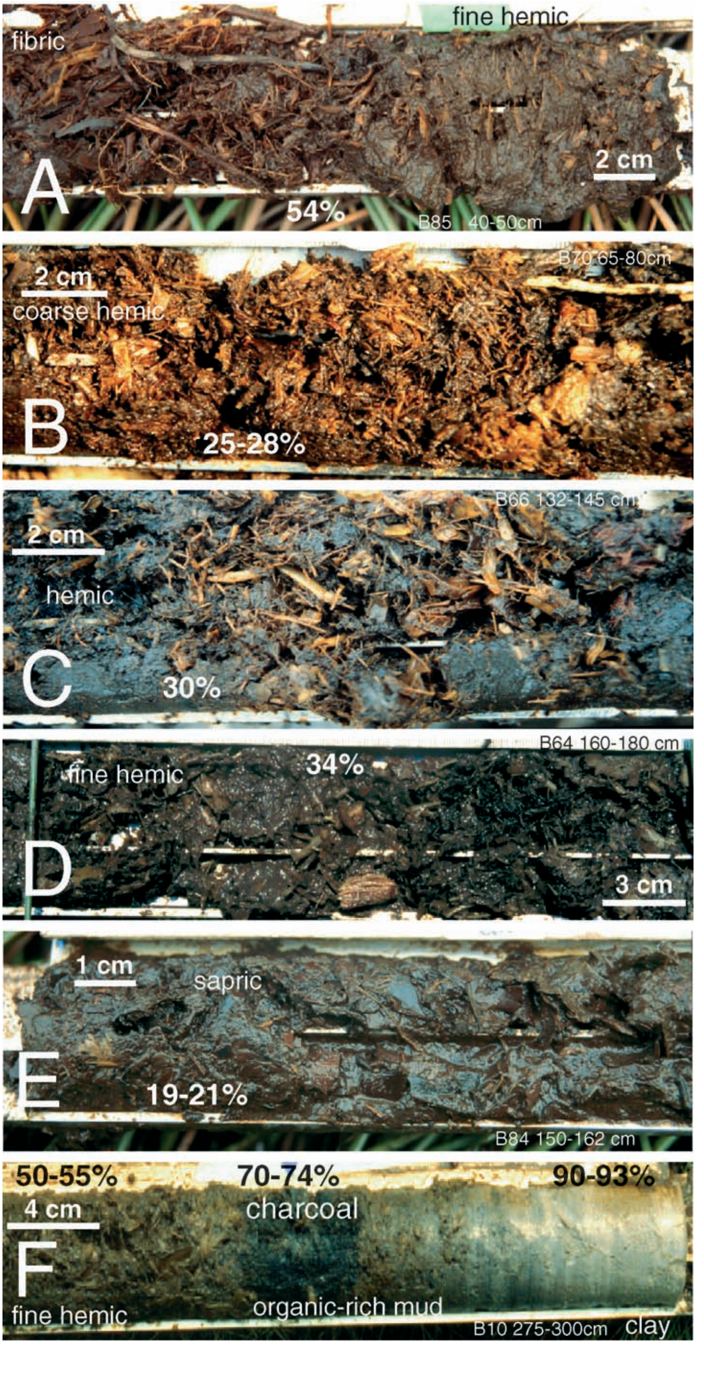
The proposed textural classification system (Table 6) for tropical soils includes the following:

Fibric organic soil material (F) has >66% fibers that are >10 mm long (Fig. 7; Table 6). It is mainly composed of long roots and woody fibers and often has little matrix. When fibric peat is compressed, clear or slightly turbid water is expelled and the volume of water is small if roots predominate. The fibers may separate and break into smaller fragments under rubbing with the fingers but do not disintegrate into a mushy substance. Usually, they retain their size on squeezing in the hand. Large woody fragments and roots >120 mm are not included in the fiber content. Fibric organic material is classified as coarse fibric (Fc) if matrix is absent (Table 6).

Hemic organic soil material (H) has 33–66% fibers >10 mm long (Fig. 7, Table 6). The amount of matrix is greater than in the fibric organic material and extruded water is turbid and reddish brown to dark brown. The peat is coarse hemic (Hc) if the organic material contains abundant long particles and fine hemic (Hf) if the plant particles are small and short.

Sapric organic soil material (S) consists of < 33% fibers and has a high matrix component which is often dark brown to black (Fig. 7, Table 6). It is strongly humified and often darker coloured than hemic or fibric organic material. In the tropics, the colour of sapric organic soils may also change rapidly on exposure to the air (oxidation). Sapric organic material becomes a paste in the hand or escapes through the fingers and has a gelatinous appearance when squeezed. It may contain long roots, fibers or wood fragments (Sw), but often has short and fine particulate matter (Ss) consisting of woody, lignin-rich material such as bark or cortex. Sapric organic soil may include some sand, silt or clay; it classifies as muck (Sm) if the ash content is 55–65%.

Fig. 7. Various peat textures of the tropical lowland mire system of Tasek Bera. (A) Fibric (left) to fine hemic (right) peat of the littoral environment with ash contents of 54%. (B) Coarse hemic peat of the littoral area with *Pandanus helicopus* as the dominant plant and ash contents between 25% and 28%. (C) Hemic peat in the littoral area with abundant *Pandanus* root fragments and ash content of 30%. (D) Fine hemic peat of the forest swamp environment with abundant small woody fragments and ash content of 34%. (E) Sapric peat of the forest swamp environment with ash content between 19% and 21%. (F) Basal section of the peat deposits in the Tasek Bera Basin; from right to left: typical progression from a kaolinitic clay with quartz grains (ash = 90–93%), to an organic-rich mud (often with charcoal fragments) with ash contents of 70–74% and to fine hemic, woody peat (ash = 50–55%).


fibric
fine hemic
2 cm
A
54%
B85 40-50cm
B70 65-80cm
2 cm
coarse hemic
B
25-28%
B66 132-145 cm
2 cm
hemic
C
30%
B64 160-180 cm
fine hemic
34%
D
3 cm
1 cm
sapric
E
19-21%
B84 150-162 cm
50-55%
70-74%
90-93%
4 cm
charcoal
F
fine hemic
organic-rich mud
B10 275-300cm
clay

Organic-rich mud (Mo) consists of organic soil material with a high mineral content (ash >65%). Distinguishing between high-ash peat (i.e., muck) and organic-rich mud in the field is difficult because of the gradual transition between the two (Fig. 7, Table 6). Silty and clay particles can be recognized upon rubbing with the fingers. However, in some highly decomposed sapric organic materials the mineral matter cannot be evaluated in the field, because of the gelatinous consistency of highly humified organic matter. Despite the problems of determining the mineral matter content of organic deposits in the field, peat with abundant mineral matter is often discernible using the Munsell soil colour chart. In the Tasek Bera Basin, organic-rich mud is usually grayish brown to dark grayish brown (10YR 4/2). Two classes of organic-rich mud are distinguished; mud with abundant fibers, root and wood fragments (Mow) and mud with few organic particles (Moo).

Mineral soil/sediment with organic material includes all soil/sediment materials with small amounts of organic matter (0–20%). The mud, clay, silt or sandy clay with organic

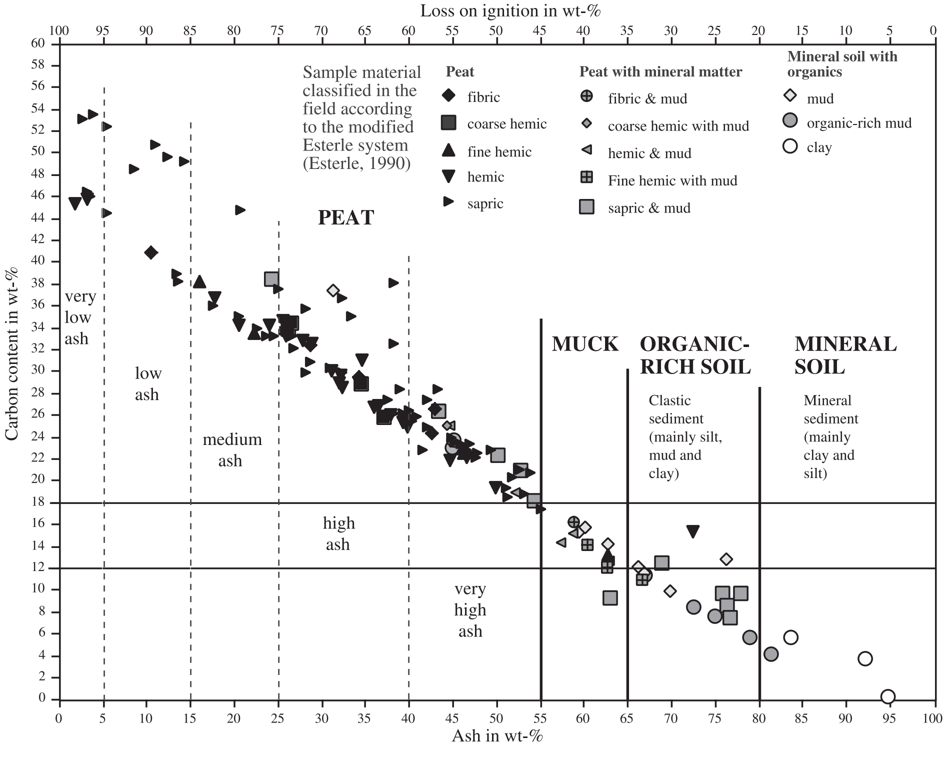


Fig. 8. Carbon versus ash content of 137 samples from 20 cores (Table 6) of the Tasek Bera Basin. The linear correlation and the definition of organic soils of the US Soil Taxonomy were used for the new proposed classification of organic deposits. Four classes can be distinguished: peat (ash = 0–55%), muck (ash = 55–65%), organic-rich soil or sediment (ash = 65–80%) and mineral soil or sediment with organic matter (ash = 80–100%). The peat class is subdivided into very low ash (0–5%), low ash (5–15%), medium ash (15–25%), high ash (25–40%) and very high ash (40–55%) peat. Fibric, hemic and sapric peats cannot be distinguished on ash content. Distinguishing peat from muck, organic-rich mud and mineral soil/sediment is, however, very accurate.

matter underlying the tropical peat deposits of Tasek Bera often has abundant root fragments and a characteristic light gray to gray colour (10YR 7/1 to 5/1) (Fig. 7F). Similar leached sediments underlying peat or coal are common in the rock record (e.g., Staub and Cohen, 1978). The uppermost clay layers often contain abundant charcoal fragments (Fig. 7F), which resulted from forest fires (mainly caused by lightning) prior to the onset of peat accumulation. Charcoal fragments are resistant to degradation and thus are concentrated in the sediments of swamp forests. In the Tasek Bera Basin, the most common substratum of the organic deposits is kaolinitic clay with quartz sand.

5.3. Proposed carbon and ash classification of peat

Our ash classification system is based on the definition of organic soils of the US Soil Taxonomy, i.e., those having at least 12–18% organic C (depending on the clay content) and the organic C and ash content of samples from the Tasek Bera Basin. These samples are ideal for development of a classification system because they cover the whole spectrum of organic C (0.6–54%) and ash (1–98%) contents of soils and sediments (Fig. 6). The samples show a linear distribution of ash versus C content (Fig. 8) and four groups can be distinguished. All samples with < 55% ash have >18% C (Fig. 8), so peat is defined as having < 55% ash. Peat is further subdivided into five classes (Fig. 9): very low ash (0–5%; LOI = 95–100%), low ash (5–15%; LOI = 85–95%), medium ash (15–25%; LOI = 75–

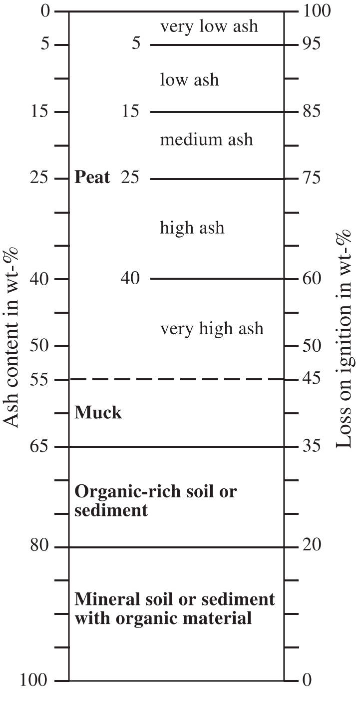


Fig. 9. The new proposed ash classification system for peat deposits based on the tropical organic deposits of Tasek Bera, West Malaysia.

85%), high ash (25–40%; LOI = 60–75%) and very high ash (40–55%; LOI = 45–60%). Organic deposits with 35–45% organic matter and high mineral matter (ash 55–65%) are called muck. These samples have C contents of 12–18%. Organic-rich soils or sediments contain 65–80% ash (LOI = 20–35%) and C contents between 6% and 16%. Mineral soils or sediments contain >80% ash (LOI = 0–20%) and approximately 0–8% C. In summary, all soils with organic matter >45% are classified as peat, those with 35–45% as muck and those with 35–20% as organic-rich soils/sediments. Mineral soils/sediments have 0–20% organic matter (Fig. 5).

Characterization of the organic deposits in the field fits the new laboratory classification based on C and ash content. The application of the 12 and 18% organic C boundaries results in a four-group classification: peat, muck, organic-rich soil/sediment and mineral soil/sediment. In the field, two groups with ash contents >65% can be differentiated, organic-rich mud and mineral soils/sediments. Organic-rich mud (often dark-coloured, humic clay-rich deposits) may contain up to 35% organic matter and hence has different physical properties from the mineral deposits. Mineral soils and sediments have < 20% organic matter and often have a high Munsell value (10YR 5 to 7). The mineral soils/sediments often have abundant root fragments but rarely contain amorphous organic matter.

6. Conclusions

The unsuccessful application of commonly used classification systems to the tropical peat deposits of Tasek Bera Basin indicates the need for a new classification scheme for tropical (woody) peat deposits. In the Tasek Bera Basin most deposits would not be considered as peat according to many classifications, even though they contain >25% C. The field texture classification proposed here is based on the Esterle classification (Esterle, 1990), which was modified from the US Soil Taxonomy and developed for tropical low-ash, ombrotrophic peat deposits and soils. It is simple and distinct and allows comparison with laboratory analyses. Differentiation of peat types is based on the visual assessment of fiber content and amorphous matrix. There are three groups of peat: fibric, hemic and sapric, which have a progressively increasing matrix content (decreasing fiber content/matrix ratio) and thus increasing degree of humification. Organic layers with high clay or silt contents are classified as organic-rich mud deposits and mineral matter-rich soils or sediments are classified as organic-rich soils/sediments or mineral soils/sediments with organic matter. The proposed texture classification applies to all organic soils with < 65% ash content (>45% LOI), i.e., peat and muck.

Most organic soils are classified according to their C or ash contents. Most systems classify peat as not exceeding 25% ash, although it is impossible to distinguish visually between peats with 20% and 35% ash. The US Soil Taxonomy (Soil Survey Staff, 1990) classifies organic soils as having more than 12 to 18% organic C, depending on clay content. A combination of the US Soil Taxonomy classification of organic soils and the ash (i.e., LOI) content, allows the discrimination of four main groups; peat, muck, organic-rich soil or sediment and mineral soil or sediment. Peat is defined as having an ash content of 0–

55% (45–100% LOI), muck 55–65% (35–45% LOI), organic-rich soils 65–80% (20–35% LOI) and mineral soils/sediments 80–100% (0–20% LOI). The peat class is further subdivided into very low ash (0–5%), low ash (5–15%), medium ash (15–25%), high ash (25–40%) and very high ash (40–55%) peat.

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