Chapter 6
Properties and Classification of the Tepui Peats

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6.1 Introduction

Tropical lowland peats develop in environments characterized by high rainfall, evapotranspiration, and temperature. Their distribution, formation, and characteristics are fairly well known from studies carried out in Southeast Asia, especially in coastal environments, and have been documented in a few comprehensive papers and documents including, among others, those by Farnham and Finney (1965), Driessen and Rochimah (1976), EKONO (1981), Lucas (1982), Bord na Mona (1984), Andriesse (1988), Mohamed et al. (2002), and Satrio et al. (2009). In contrast, knowledge about the origin and features of tropical highland peats is still lagging behind.

Tropical highland peats form and evolve in climatic environments close to temperate, with surplus rainfall, but lower temperature and evapotranspiration than in the lowlands. In the Guayana Highlands, peats have formed along an elevation gradient spanning roughly from 600 m to 2,900 m a.s.l. They have been studied in the eastern highlands from a paleogeographic point of view using radiocarbon dating (Schubert and Fritz 1985; Rull 1991; Schubert et al. 1994; Nogué et al. 2009) and pollen analysis (Rull 1991, 2004, 2005; Nogué et al. 2009). However, little is known about their morphological, physical, and chemical characteristics, and their taxonomic classification. So far, only a few isolated highland peat profiles have been systematically described in the field and characterized in laboratory (e.g., CVG 1991; Ramos 1997). This study contributes to filling this information gap.

Peats in the Guayana Highlands show a fragmented distribution pattern. They are located in depressions and on gentle slopes receiving regular water supply that ensures that the sites are permanently waterlogged. Peatlands are mosaics comprising many small peat areas that have important contribution to local and regional hydrology. The accumulation of organic materials is favored by high rainfall, water stagnation or restricted flow, type of vegetation cover and development, very low water pH, and relatively low temperature. Under these environmental conditions,

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the production, accumulation, and preservation of biomass are greater than its chemical breakdown. Organic soils are often associated with organomineral soils, both resting on lithic substratum at variable depth and surrounded by large rocky terrains.

Highland peats are formed by organic debris coming from a variety of plants (grasses, forbs, shrubs, and small trees) and include roots, branch and stem fragments, leaves, flowers, and seeds, with variable addition of mineral materials. They usually have dark brown to black color, distinctive odor common of decaying vegetation, and spongy and very friable consistence. Root content decreases with depth. Stages of organic matter decomposition vary from the surface to the bottom. Commonly, the top layers are made up of younger, fibrous, and very highly compressible materials with little breakdown. Subsurface layers are slightly to moderately decomposed, and basal layers are usually the most decomposed.

This study reports on the properties of peatsoils that have developed on sandstone–quartzite mesetas (tepuis) and igneous–metamorphic massifs in the western Guayana Highlands. Visited sites are distributed over three study areas, all located in the western portion of the Amazonas state: (1) the Marahuaka-Huachamakari massif, (2) the Cuao-Sipapo massif, and (3) the western border of the Maigualida massif. Twelve organic soils and three organomineral soils were described in the field following the FAO guidelines for profile description (FAO 1990), with ad hoc adaptations for the description of organic soils. Site features and profile characteristics are reported in the Appendix of this volume. Samples were analyzed in laboratory for physical and chemical characterization according to the methods described and discussed in Schargel et al. (2011). Full determination results are presented in the Appendix. Soils were classified using the Soil Taxonomy (Soil Survey Staff 2006) and the WRB systems (FAO 2006). Univariate statistical analysis was performed for individual layers or full profiles (average estimates) depending on sample size. Statistical parameters were calculated for sample sizes of five or larger. Some soil properties with incomplete datasets, referring for instance to organic matter content, organic matter ratio, and base+aluminum saturation, were estimated for whole profiles. Simple correlation analysis was carried out on physical and chemical properties to establish affinity relationships.

This chapter describes and discusses the morphological, physical, and chemical properties of the peatsoils in the western Guayana Highlands together with their spatial variations. Taxonomic classification of the soils is presented and issues related with the classification are discussed.

6.2 Morphological Features

Most Guayana Highland peats show gradual layer variations that result from increasing organic matter decomposition with depth. Other variations in profile layering and layer features are controlled by the position on the landscape, the drainage conditions depending on the nature of and depth to bedrock, and differences in age of the peat materials. Most profiles consist of several organic layers differentiated by the degree of organic matter decomposition or humification. Peatsoils were described and classified in the field according to visual features such as color, texture, degree of wetness, root and fiber content, thickness, and layer boundaries. Root description was given special attention in terms of color, size, amount, state (live and dead), distribution pattern (vertical and horizontal), and degree of decomposition, using visual and touch appraisal. Morphological features were described according to the Soil Survey Manual (Soil Survey Staff 1993). Master horizons and layers (i.e., Oo, Oi, Oe, Oa, and A) were identified following criteria from the Soil Taxonomy (Soil Survey Staff 2006) and Soil Survey Manual.

6.2.1 Layer Types and Sequences

In the field, organic layers were identified using the following criteria:

- Folic Oo layers are made up of fresh organic residues, particularly leaves with different degrees of decomposition, live and dead roots, and fragments of branches and stems, forming a mat of variable thickness and spatial continuity.
- Fibric Oi layers are distinguished by their brownish color, poorly decomposed plant residues, live and dead roots with white and light yellow colors, and readily identifiable plant and root tissues.
- Hemic Oe layers are formed of partly decomposed plant residues that are at a stage of decomposition intermediate between those of Oi and Oa layers; with very dark colors; lower amount of roots, most of them being dead and having whitish colors; and slightly sticky organic materials, sometimes with admixtures of mineral sediments. Although water-saturated, these layers show very friable consistence and massive structure.
- Sapric Oa layers are formed of well-decomposed plant residues whose origin can no longer be identified; root content is very low in most soil profiles and the few identifiable roots are dead; most layers are very dark, friable, massive, and slightly adhesive.

Usually, organic layers have compact structure, but are only slightly plastic, providing foothold for the kind of mainly low vegetation stand they support. More plastic layers always contain larger amounts of mineral material (organomineral horizons and soils).

Rubbed and unrubbed fiber contents were taken into account for final identification of the organic layers. For many samples, rubbed and unrubbed fiber contents as determined in laboratory were relatively lower than field contents. For that reason, the field data were often preferred to identify the layers and group them for further analysis. The difference between field and laboratory data may have resulted from fiber decomposition during the relatively long time elapsed between sampling and determination. Also quartz-sand particles present in many samples possibly contributed to fiber fragmentation during the treatments. When determining fiber content in organic materials high in mineral matter, rubbed fibers were mostly quartz sand. On the basis of field observations, the following criteria were used to separate layers:

- Oi layer: more than 66% unrubbed fibers by volume
- Oe layer: 33–66% unrubbed fibers by volume
- Oa layer: less than 33% unrubbed fibers by volume

Variations in layer arrangement are largely controlled by profile position on the landscape. Peatsoils on (pseudo-)karstic landforms show commonly an Oo–Oi–Oe layer sequence. Some soil profiles exhibit Oi–Oe or, more locally, Oi–Oe–Oa sequences. Organic layers rest on sandy and fine gravelly material derived from rock weathering (Cr horizons) or directly on the bedrock (R). At slightly better drained sites such as colluvial glacis and stepped landforms, umbric A horizons sometimes overlie or underlie Oe layers, or rest on C horizons (A–Oe, Oe–A, and A–C sequences). Soils on narrow floodplains have Oi layers underlain by mineral materials with variable textures, including sand, silt loam, and silty clay loam (Oi–C). The thickness of the soil profiles above the lithic substratum, including organic and mineral materials, varies from 40 to 150 cm. Figures 6.1–6.4 illustrate the layer and horizon sequences of the soil profiles described at the different study sites, with distinction between sequences of Oo–Oi–Oe layers (Fig. 6.1), Oo–(Oi) Oe–Oa layers (Fig. 6.2), and Oo–Oi–Oe–Oa layers (Fig. 6.3). Figure 6.4 shows the horizonation in organomineral profiles.

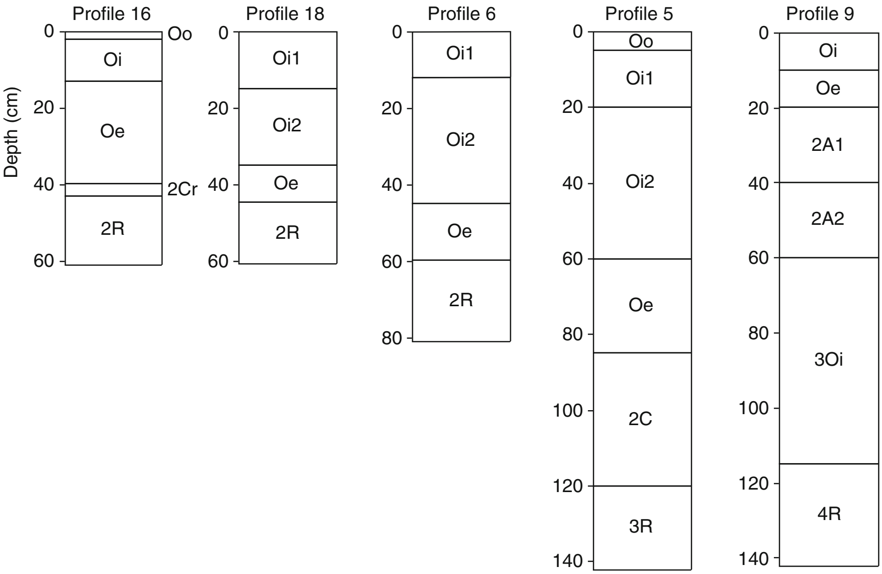


Fig. 6.1 Peat profiles with Oo–Oi–Oe layers sequence

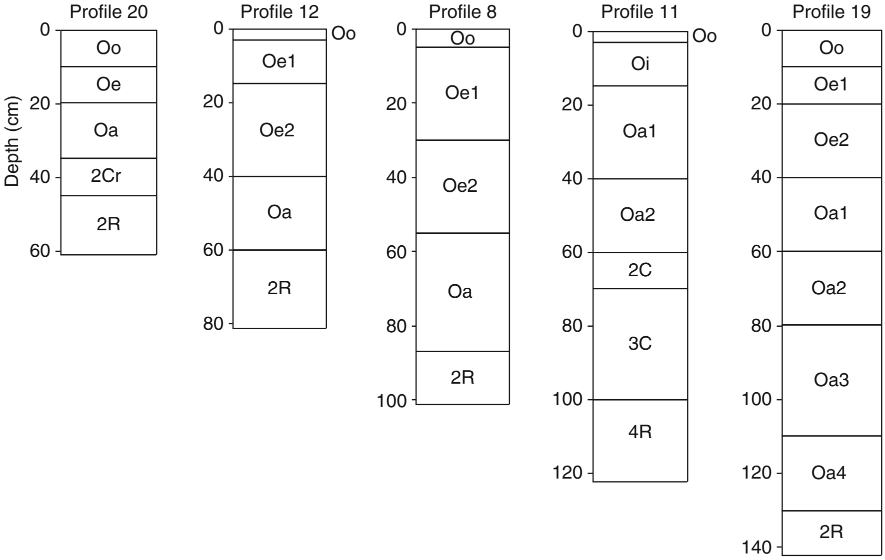


Fig. 6.2 Peat profiles with Oo–(Oi)Oe–Oa layers sequence

The upper peat layers in tepui environment are less decomposed than the deeper ones, in contrast to what happens usually in most tropical and subtropical lowland peats where the stages of decomposition decrease with depth (Zelazny and Carlisle 1974; Driessen and Rochimah 1976; Andriesse 1988). Variations in thickness per type of layer and horizon are shown in Table 6.1. In general, thickness variations of the organic layers tend to decrease from the surface Oi (CV of 74%) to the subsurface Oe and Oa layers (CV around 60%). The Oi layers are 25 cm thick on average and lie usually at the soil surface, but may also occur buried. They contain a dense mat of live and dead roots, from very coarse to very fine, and some leaves in different stages of decomposition. The Oe layers are 23 cm thick on average and start at 3–60 cm depth from the soil surface. Root content is fairly similar to that of the Oi layers; roots are medium to very fine and horizontally distributed. Structure is massive. Most Oi and Oe layers are nonplastic and nonsticky. The Oa layers are 45 cm thick on average. They start at 15–110 cm depth from the soil surface and extend to 80–150 cm depth in some profiles. In general, Oa layers are the deepest organic materials in the layer sequence, close to the bedrock or to sandy C horizons. They include very few roots, and are massive, slightly plastic, and slightly sticky.

Some profiles have mineralized umbric A horizons, 28–40 cm thick and starting at 0–20 cm depth from the soil surface. They have few to many, fine to medium, live and dead roots. Structure is blocky, and consistence is slightly sticky and slightly plastic. At some locations, the organic tier overlies sandy or finer-textured C horizons that start at 13–85 cm depth from the soil surface. The thickness of the

Fig. 6.3 Peat profiles with Oo–Oi–Oe–Oa layers sequence

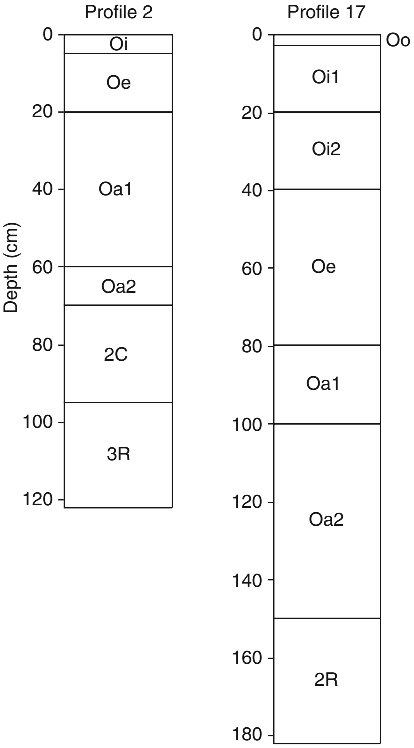
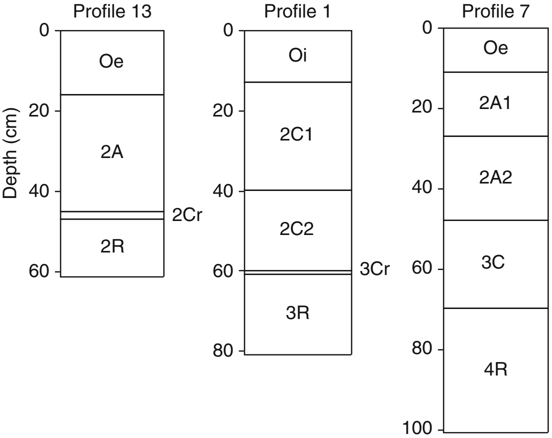


Fig. 6.4 Organomineral profiles



C horizons is 29 cm on average, but varies from 2 to 107 cm. Underlying the mineral C horizons is the bedrock, starting at 40–150 cm depth from the soil surface.

Table 6.1 Morphological features of organic and organomineral layers

Layer	Statistics	Thickness (cm)	Roots dry weight (%)	Munsell colors most common
Oi	*n*	9	6	10YR4/1; 10YR2/2; 5YR2.5/1; 2.5Y2/0
	Range	5–55	3.7–14.2	
	Mean	24.7	9.0	
	SD	18.3	4.0	
	CV (%)	74.1	44.4	
Oe	*n*	13	10	10YR2/2; 10YR2/1; 2.5Y2/0; 7.5YR4/2; 5YR2.5/1; 5YR3/1
	Range	10–50	1.6–16.8	
	Mean	22.7	8.4	
	SD	13.3	6.2	
	CV (%)	59.6	73.8	
Oa	*n*	7	5	10YR2/1; 10YR2/2; 2.5Y2/0; 5YR2.5/1
	Range	15–90	1.2–7.2	
	Mean	44.6	3.6	
	SD	28.1	2.9	
	CV (%)	63.0	80.5	
A	*n*	6	3	10 YR2/1; 2.5Y2/0; 10YR3/1
	Range	28–40	1.1–2.7	
	Mean	25.8	1.8	
	SD	12.8	–	
	CV (%)	49.6	–	

6.2.2 Root Content

Roots vary with soil depth in terms of quantity, size, distribution pattern (vertical or horizontal), and state (proportion of live and dead roots). As peats are dominantly covered by meadow vegetation and, to a minor extent, by grassland, living roots usually concentrate in a dense surficial mat (0–15/20 cm). Some roots go down to 50–60 cm; below this depth, only few shrub roots were found. A common vertical sequence of layers and root distribution based on visual estimation in the field is as follows:

- Oi layers: many roots, from fine (1–2 mm) to very coarse (10 mm or larger), vertically distributed, mainly live, and some dead slightly decomposed.
- Oe layers: moderately few to common and sometimes many roots, fine (1–2 mm) to medium (2–5 mm), vertically and horizontally distributed, commonly dead, and moderately decomposed.
- Oa layers: very few to few roots, fine and very fine (<1 mm), commonly dead, and strongly decomposed.

In general terms, root content decreases with soil depth (Fig. 6.5). There is no clear difference in average root content between Oi and Oe layers, but the amount of roots drops substantially in the Oa layers, being about 60% lower than in the overlying layers (Table 6.1). If the whole layer population is taken into account, the root content drops by 41–94% between the top of the Oi layers and the bottom

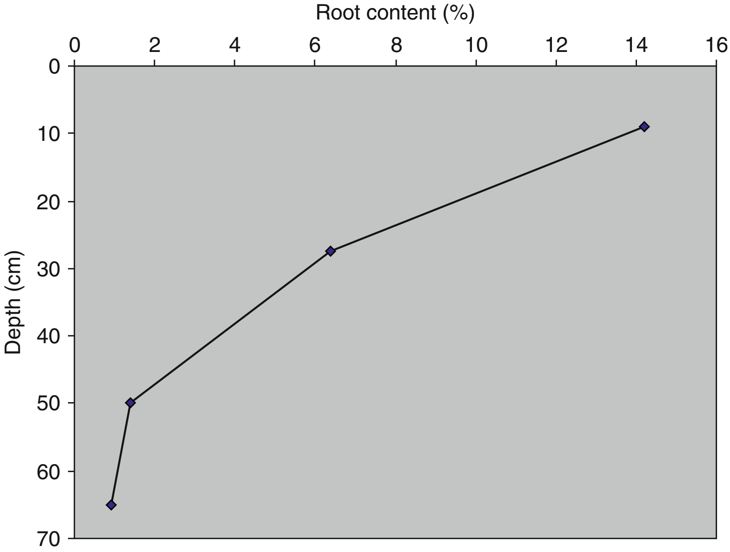


Fig. 6.5 Variation of root content with depth in peatsoil P11 (% moist roots in field moist material)

of the Oe layers. This reflects greater root growth in the surface layers and increasing decomposition of the organic residues with depth as a result of layer age. Relative variability increases from surface layers (CV of 44%) to subsurface tiers (CV of 74–81%) as a consequence of wider root content ranges. Low root content in some A horizons could indicate faster humification taking place in soils on better drained landforms (e.g., colluvial glacis and alveoli on stepped terrains).

Although live and little decomposed roots were removed prior to physical and chemical analyses, root content and organic matter content by ignition show moderate, positive correlation ($r = 0.39$). Most likely, only the coarser roots were removed and a significant proportion of the organic matter is accounted for by the remaining root mass. In some layers, the amount of dry matter removed with the weakly decomposed roots is quite high, close to 30% of the total dry matter.

The presence of thick surficial root mats in the Oo and upper portion of the Oi and Oe layers may result from waterlogging and oligotrophic conditions of the surface organic tier. This dense carpet of organic litter is an important feature of the Guayana peats, indicating that nutrient cycling basically occurs in the upper leaf and fibrous litter layers (Oo and Oi layers) which behave as the acrotelm stratum, rather than in the deeper permanently waterlogged peat, the catotelm stratum.

6.2.3 Soil Color

There are slight color differences between organic layers (Table 6.1). The color value tends to decrease from top to bottom of the soil profiles. The Oi layers vary between dark gray and very dark brown, although black layers can occur at the soil surface. In the Oe and Oa layers, the dominant colors are black and very dark brown. Hues of 10YR and 2.5Y are the most common in the soil matrix. Reddish hues (5YR and 7.5YR) occur in Oi and Oe layers of soils formed on granodiorite, reflecting the effect of the iron oxides released by the weathering of the mafic rock minerals. Iron oxides form quelate complexes with the organic matter that can be leached and deposited on the colloidal particles of the soil matrix. Hues of 10YR, 7.5YR, and 5YR predominate in the subsurface organic tier, indicating stronger chemical decomposition. Lighter colors in the Oi layers reflect a lower degree of decomposition and higher fiber content relative to deeper layers.

Surface A horizons are lighter colored (10YR 3/1) than subsurface ones (10YR 2/0, 10YR 2/1). Surficial A horizons form under better drainage conditions and with higher mineralization than the buried A horizons. The dark color of the latter is caused by colloidal substances percolating from the upper layers.

6.2.4 Drainage Conditions

Peats are extremely soft and unconsolidated surficial deposits and are water-saturated the largest part of the year. The water table is usually near or above the ground surface. Soils on colluvial fans and stepped slopes have deeper water table (80–90 cm depth) or have wet nonsatiated organic layers in response to better drainage conditions. Water surplus due to high rainfall and low evapotranspiration, low hydraulic conductivity, water retention by the organic materials, and sloping topography contribute to the concentration, accumulation, and ponding of surface water in depressions giving rise to peat bogs (Fig. 6.6).

6.3 Physical Properties

In Table 6.2, the physical property data are presented per type of organic layer and organomineral horizon. These data have been averaged to provide an overall characterization of all organic layers together in Table 6.3 and all organomineral horizons together in Table 6.4. Physical soil properties are moderately to highly variable. In general, the most significant and abrupt changes occur at 15–30 cm depth. Because of sampling and laboratory constraints, some layers lack physical data causing differences in sample size (Table A.4 in Appendix).

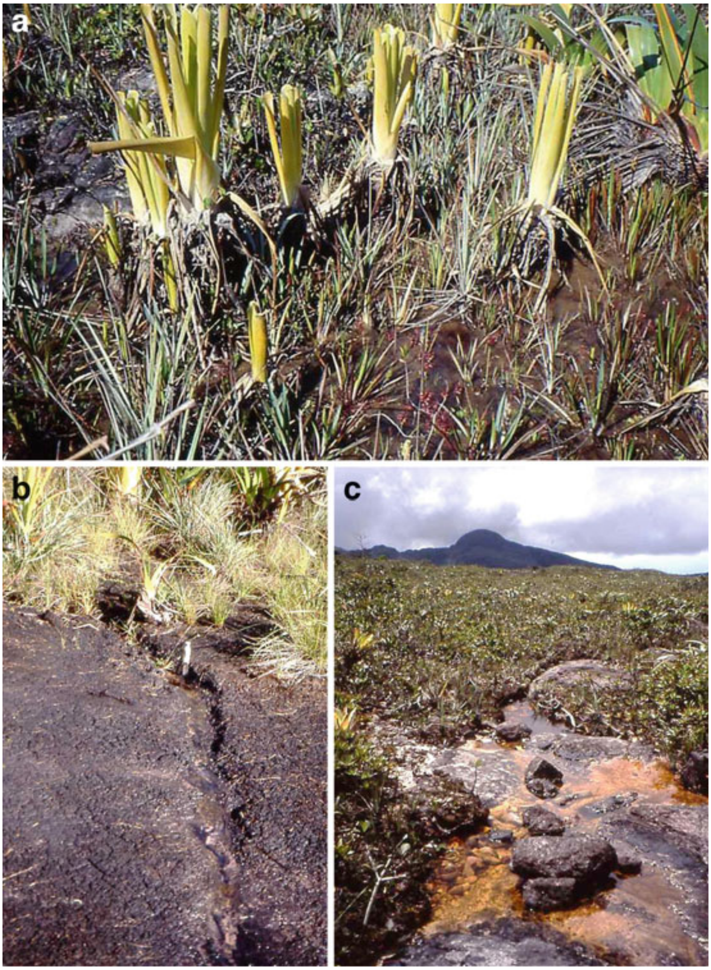


Fig. 6.6 Peatland drainage features. Peatlands are water-saturated over the year with patches of free water at the peat surface (**a**; *Brocchinia*, *Stegolepis, Drosera*, among others). Excess water is evacuated by small outlets (**b**) or by blackwater creeks (**c**) according to the size of the peat area (photos Zinck)

6.3.1 Dry Matter and Fiber Contents

Dry matter consists of both the organic and mineral materials after oven drying the field moist soil samples at 110°C. Average values and ranges of dry matter are as follows: 12% (5–30%), 12% (3–35%), and 16% (2–49%) in Oi, Oe, and Oa layers, respectively (Table 6.2). In most soils, dry matter increases and field water content decreases with soil depth, except in profile P19, which has very high field water

Table 6.2 Physical properties of organic and organomineral layers

Layer	Statistics	Dry matter (%)	NRF1 (%)	NRF2 (%)	NRF3 (%)	Rubbed fiber (%)	Mineral content (%)	Bulk density at field moisture (Mg m^{-3})	Bulk density of dry sample (Mg m^{-3})	Field water content (%)
Oi	*n*	10	9	9	6	9	10	9	1	12
	Range	5.3–30.2	20–60	10–50	5–40	5–50	0–77	0.56–0.70	–	231–1,782
	Mean	12.4	42.2	30	20.8	15.6	29.0	0.56	0.11	1,026
	SD	8.2	14.8	16.6	12.8	17.3	30.0	0.05	–	460
	CV (%)	66.1	35.1	55.3	61.5	110.9	103.4	8.9	–	45
Oe	*n*	16	13	13	12	13	17	10	2	15
	Range	2.6–35.3	5–60	5–60	5–40	5–40	0.86–83.6	0.54–0.78	0.10–0.23	183–3,710
	Mean	12.4	36.5	27.7	22.5	15.8	26.3	0.64	0.17	1,170
	SD	8.9	19.1	15.8	11.8	11.8	31.9	0.09	–	918
	CV (%)	71.7	52.3	57.0	52.4	74.7	121.3	14.1	–	78
Oa	*n*	10	8	8	7	8	9	5	3	10
	Range	1.9–48.7	5–50	5–50	5–40	5–20	7.3–84.8	0.56–0.76	0.14–0.23	106–5,229
	Mean	15.8	16.8	13.8	10.7	6.8	31.2	0.64	0.20	1,532
	SD	15.1	14.8	14.8	13.0	5.3	30.3	0.09	–	1,899
	CV (%)	95.6	88.1	107.2	121.5	78.0	97.1	14.1	–	124
A	*n*	6	3	3	3	3	7	3	2	7
	Range	35.2–76.2	50–60	30–50	30–40	5–30	71.3–97.1	0.66–0.76	0.78–1.34	17–184
	Mean	57	53.3	40.0	36.7	21.7	88.4	0.71	1.06	79
	SD	16.3	–	–	–	–	9.5	–	–	61
	CV (%)	28.6	–	–	–	–	10.7	–	–	77

Dry matter: organic and mineral materials after oven drying the field moist soil samples at 110°C; NRF1 to NRF3: nonrubbed fibers in three steps of increasing treatment intensity; Mineral content: mineral content after ignition at 110°C and 400°C; FWC: soil water content at field condition

Table 6.3 Variability of the physical properties in the organic layers

Statistics	Roots (%)	Dry matter (%)	NRF1 (%)	NRF2 (%)	NRF3 (%)	RF (%)	Bulk density at field moisture (Mg m^{-3})	Bulk density of dry sample (Mg m^{-3})	Mineral content (%)	Organic content (%)	Field water content (%)
n	21	36	30	30	25	30	25	6	35	38	36
Range	1–16.8	1.9–48.7	5.0–60	5.0–60	5.0–40	5.0–50	0.54–0.78	0.1–0.24	0–84.8	15.2–100	106–5,229
Mean	7.4	13.3	33	24.7	18.8	13.3	0.63	0.18	26.7	74.3	1,226
SD	5.3	10.6	19.1	16.6	13	12.7	0.07	0.06	29.1	28.5	1,171
CV (%)	71.6	79.7	57.8	67.2	69.1	95.5	11.1	33.3	108.9	38.4	96

NRF1 to NFR3: nonrubbed fibers in three steps of increasing treatment intensity; RF: rubbed fibers

Table 6.4 Variability of the physical properties in the organomineral horizons

Statistics	Roots (%)	Dry matter (%)	NRF1 (%)	NRF2 (%)	NRF3 (%)	RF (%)	Bulk density at field moisture (Mg m^{-3})	Bulk density of dry sample (Mg m^{-3})	Mineral content (%)	Organic content (%)	Field water content (%)
n	5	13	3	3	3	3	3	2	14	14	14
Range	0.9–2.7	20.3–76.2	50–60	30–50	30–40	5–30	0.66–0.76	0.78–1.34	42.7–97.8	2.2–57.3	17–392
Mean	1.44	52.4	53.3	40	36.7	21.7	0.71	–	85	15	117
SD	0.76	18.4	–	–	–	–	–	–	14.3	14.3	111
CV (%)	52.8	35.1	–	–	–	–	–	–	16.8	95.3	95

NRF1 to NFR3: nonrubbed fibers in three steps of increasing treatment intensity; RF: rubbed fibers

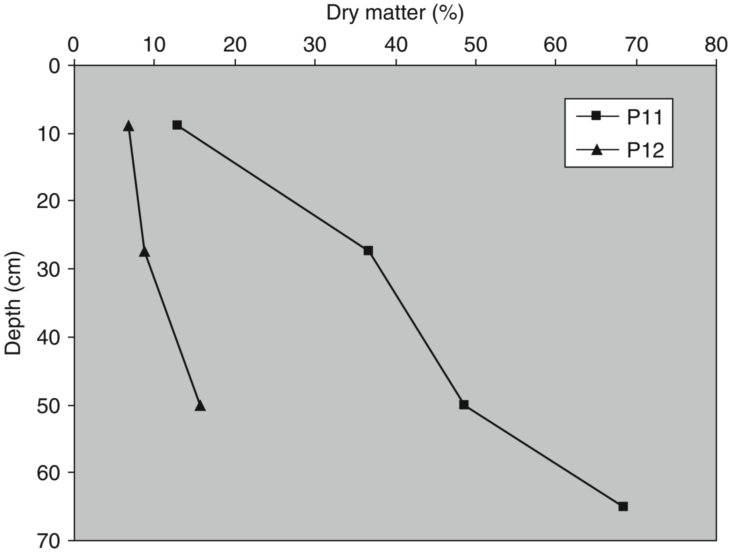


Fig. 6.7 Variation of dry matter content with depth in peatsoils on sandstone (P11) and granite (P12)

content even in the deeper, permanently saturated layers. Dry matter content increases also in the relatively better drained A horizons, especially toward the underlying C horizons. Pore space and field water content decrease markedly with increasing mineral matter, as reflected by wet and dry bulk densities. In older peat layers (e.g., P8, P12, and P17), dry matter content increases and field moisture content decreases as a consequence of the loss of pore space with age and depth. Figure 6.7 shows the vertical variation of dry matter content in peats on sandstone and granite, respectively.

Rubbed fiber content is an indicator of the physical decomposition of the organic materials and relates to physical and chemical processes occurring in the soil as a consequence of peat evolution with age (Boelter and Blake 1964; Boelter 1969; Nichols and Boelter 1984). Clear and precise layer delimitation and characterization based on fiber content were difficult due to high levels of water saturation and the presence of water tables. According to visual appraisal in the field, most peats show a physical decomposition of the fibers in the hemic range. In general, unrubbed and rubbed fibers decrease with soil depth, indicating that fiber decomposition is weak in the surface peat layers, but increases with depth close to the mineral C horizon or the lithic contact. These results agree with those reported by D’Amore and Lynn (2002), who noted increasing organic matter decomposition below the fibric surface layers in natural undrained Histosols.

Rubbed fiber amounts to about 16% in both Oi and Oe layers, but only 7% in Oa layers (Table 6.2). In contrast to this general trend, the rubbed fiber content increases with soil depth in a few young peat profiles, as for instance profile P18 that shows a marked fiber increase from 35 to 45 cm downward. In some profiles (e.g., P9, P10, P11, P12, P13, and P17), the values of rubbed and nonrubbed fiber are relatively low in the upper layer exposed to seasonal fluctuation of the water table that favors the decomposition of the organic materials.

Fiber determination strongly depends on the strength of the laboratory treatment applied. For instance, between treatment 1 and treatment 3, as described in Schargel et al. (2011), the unrubbed fiber estimates decrease by about 51, 38, and 36% for the Oi, Oe, and Oa layers, respectively (from NRF1 to NRF3 in Table 6.2). Although rubbed fiber shows the presence of quartz sand in most layers, the latter is really important and dominant in layers rich in mineral matter (e.g., 0–60 cm in P9, 0–5 cm in P10, and 15–60 cm in P11). Sand coarser than 0.15 mm that is retained on the 100-mesh sieve can contribute to the breakdown of fibers during the rubbing procedure and in treatment 3 of unrubbed fiber. Coarse sand particles are infrequent in most of the organic soils, but they are often an important component in the small and shallow peat deposits surrounding rock outcrops. Separating the coarser mineral matter by decantation is essential for fiber determination in these soils.

Although the vegetation of the peatsoils does not vary substantially in terms of taxonomic composition, differences were found in the proportions of herbaceous (tepuian grassland and meadows) and woody components (tepuian forests, bushes, and shrubs). This controls the age of the plant residues and the biochemical composition of their tissues in terms of being mainly composed by either more resistant ligneous debris or, on the contrary, readily decomposed litter. These differences affect the natural breakdown of organic materials and the proportion of rubbed fiber as an indicator of the degree of decomposition of the organic materials.

6.3.2 *Mineral Content*

The mineral content consists of the plant residue ash and the mineral particles that remain after organic matter has been removed on ignition at 400°C, expressed on oven-dry weight basis (Davies 1974). Mineral content increases globally with soil depth in most of the peatsoils. Average values decrease first slightly from Oi (29%) to Oe (26%) layers and then increase in the Oa layers (31%) (Table 6.2). Mineral matter content in the organic layers is highly variable, ranging from nothing to about 85%. It is much less variable in the organomineral A horizons and usually higher than 80%. Variations in mineral content are mostly related to the geomorphic processes that favored the accumulation of mineral matter in low-lying landscape positions, together with the accumulation and preservation of the organic residues. Terric materials can have different origins, including in situ rock weathering, admixture of colluvial sediments coming from surrounding rocky terrains, and alluvial deposits intercalated with organic layers in small

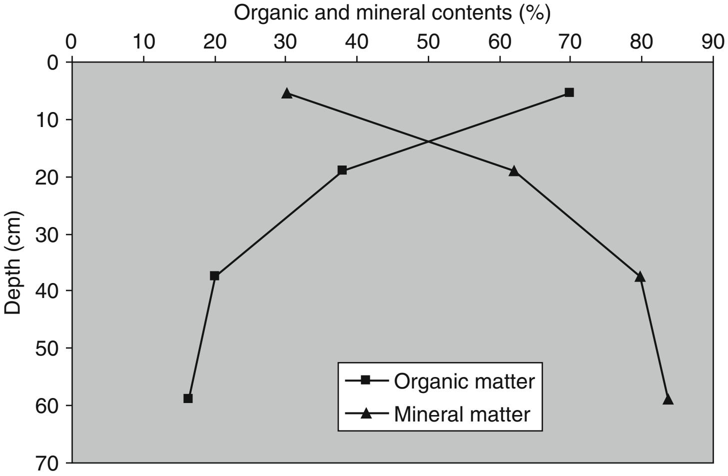


Fig. 6.8 Variation of organic matter and mineral matter contents in peatsoil P5 on sandstone

floodplains. The inclusion of mineral matter in peats is common in mountain peatlands exposed to receiving erosion debris from upslopes (Chimner and Karberg 2008). Mineral matter also results from organic matter decomposition but to a lesser extent. Higher amounts in Oa layers can be associated with increased decomposition of the organic material and the transition to the underlying mineral layers. Mineral contents and organic matter contents by Walkley–Black are closely and negatively correlated ($r = -0.59$). The pattern of mineral content increment with depth in an organic soil developed on sandstone is shown in Fig. 6.8.

6.3.3 Bulk Density

Soil bulk density was determined using two different procedures: from samples at field water content (i.e., water-saturated samples) and from oven-dry samples. Samples were taken in the center of the natural profile layers delineated in the field. Additionally, some samples were collected at 10 cm intervals at 0–40 cm depth in profiles P8, P9, and P12 to assess changes in bulk density at constant depth variation. These samples were oven dried, and bulk density was calculated on a volume base of 125 cm^3.

Wet bulk density is the physical parameter with the lowest variability. In most soils, bulk density at field moisture slightly increases with depth in the organic layers, with average values of 0.56 Mg m^{-3} in Oi layers and 0.64 Mg m^{-3} in Oe and Oa layers (Table 6.2). In some cases, the values decrease in deeper layers. Wet bulk

Table 6.5 Bulk density of dry samples

Soil profile	Layer	Depth (cm)	Bulk density (Mg m^{-3})
P8	Oo–Oe	0–10	0.04
	Oe	10–20	0.05
	Oe	20–30	0.07
	Oe	30–40	0.06
P12	Oo–Oe	0–10	0.08
	Oe	10–20	0.091
	Oe	20–30	0.091
	Oe	30–40	0.094
P9	Oi	0–10	0.23
	Oe	10–20	0.29
	A	20–30	0.63
	A	30–40	0.81

density values range from 0.54 to 0.78 Mg m^{-3}, without significant variability differences between types of organic layer. Bulk density values of the A horizons are similar to those of the organic layers in spite of larger mineral contents. The high proportion of water per soil volume obscures the differences in bulk density between organic and mineral materials.

Dry bulk density was determined on a few samples only. Average values vary with depth from 0.11 to 0.17 to 0.20 Mg m^{-3} in Oi, Oe, and Oa layers, respectively (Table 6.2). Dry bulk density variations in samples collected at 10 cm intervals reflect the proportion of organic matter in the samples (Table 6.5). In profiles P8 and P12 with more than 90% organic matter content, the values of dry bulk density range from 0.04 to 0.09 Mg m^{-3} with slight increases with depth, while in profile P9 bulk density varies from 0.23 to 0.81 Mg m^{-3} related with organic matter contents decreasing from 83 to 15% with depth. These values are in agreement with those reported by Andriesse (1988) and D'Amore and Lynn (2002). They are also partially in line with the data provided by Driessen and Rochimah (1976), and Tie and Kueh (1979) for lowland peats from Malaysia and Indonesia, showing bulk density values of less than 0.1 Mg m^{-3} in fibric peats and 0.13–0.2 Mg m^{-3} in sapric peats.

The low bulk density of the peat materials in our study area is related to the high pore space occupied by water. The permanently waterlogged layers are only slightly compacted with depth. In the surface layers, bulk density values are also low because of the abundance of large and irregular pores, many of them being probably root channels as already noted by Caldwell et al. (2007) in peatlands from southeastern USA. In contrast, in many tropical lowland peats, bulk density is higher in the surface than subsurface layers because of more advanced organic matter decomposition. Furthermore, bulk density determined at field water content increases with increasing mineral content ($r = 0.58$) because part of the total pore space is occupied by mineral matter. Large mineral contents in A horizons cause dry bulk density to increase (0.78–1.34 Mg m^{-3}).

Bulk density is related to organic matter content, with $r = -0.40$ for organic matter by Walkley–Black (OM1) and $r = -0.57$ for organic matter by ignition (OM2). The weight loss on ignition explains better the effect of organic matter on bulk density than the data provided by the other method. In fact, OM1 is not considered a good estimator of organic carbon in organic soils. The correlation of bulk density to the differences between OM2 and OM1 values gave a coefficient of −0.52. Smaller differences were found in soils with lower organic matter content by ignition.

6.3.4 Field Water Content

The field water content (FWC %) represents the difference in weight between the soil sample at (saturated) field conditions and the sample oven dried at 105°C. Average FWC values are 1,026, 1,170, and 1,532% for Oi, Oe, and Oa layers, respectively (Table 6.2). FWC is highly variable among individual organic layers and whole profiles, with extreme recorded values of 106 and 5,229%. The above-mentioned FWC averages obscure the fact that, in most soil profiles, field water contents actually decrease with depth from hemic to sapric layers, in agreement with similar results obtained by Katimon and Melling (2007).

Field water content is related to other physical and chemical properties. FWC decreases with increasing dry matter content ($r = -0.71$) and increasing mineral matter content ($r = -0.43$). FWC correlates with organic matter contents by Walkley–Black (OM1) and by loss on ignition (OM2) at $r = 0.53$ and $r = 0.43$,

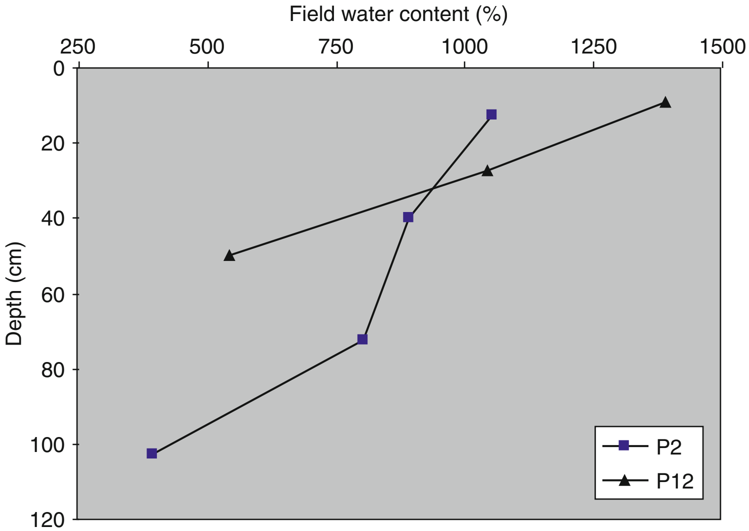


Fig. 6.9 Variation of field water content with depth in peatsoils on sandstone (P2) and granite (P12)

respectively. Water content increases as bulk density decreases ($r = -0.58$). Field water contents of peatsoils on sandstone and granite are compared in Fig. 6.9. Levels of FWC in organomineral soils are significantly lower than those in organic layers (Table 6.2).

6.4 Chemical Properties

In Tables 6.6 and 6.7, the chemical property data are presented per type of organic layer and organomineral horizon, respectively. These data have been averaged to provide an overall characterization of all organic layers together in Table 6.8 and all organomineral horizons together in Table 6.9. Some layers lack chemical determinations causing differences in sample size that can affect the statistical analysis. The full dataset used for describing and assessing the chemical properties is shown in Table A.5 in the Appendix. The peatsoils vary markedly in organic matter content from nearly pure organic material (e.g., P17) to layers borderline to mineral soils. Trend analysis with soil depth is based upon the different organic layers as identified in the field.

6.4.1 Organic Matter Content

Average organic matter content in organic layers is 74% by loss on ignition (OM2) and 28% using the Walkley–Black method (OM1) (Table 6.8). OM1 and OM2 are moderately correlated ($r = 0.47$), while OM1 shows a moderate negative correlation with mineral material ($r = -0.33$). In general, OM1 values are substantially lower than OM2 values. The average OM2:OM1 ratio for all sampled organic layers is 3.8. However, in a few layers with high mineral content in profiles P7, P9, P11, and P13, OM1 values resulted to be larger than OM2 values. This is an unlikely outcome, most probably due to insufficient ignition of samples containing mineral material that prevented the organic matter from full combustion.

In general, organic matter contents decrease with peat depth (Fig. 6.10). The decrease is more pronounced for OM2 than for OM1 in most soils high in organic matter (profiles P8, P12, P17, P18, and P19). Lee et al. (1988) found that the easily oxidizable organic carbon, obtained using the Walkley–Black procedure, remained relatively constant with depth in fibric, hemic, and some sapric materials, decreasing only in the most decomposed sapric material. In general, changes in organic matter content with depth are more related to the mixture of organic and mineral materials along the profiles than to the decomposition of the organic materials.

Peat materials vary spatially, with amounts of organic matter higher than 90% at some sites (P8, P12, P16, P17, P18, and P19). On average, OM2 values are spatially less variable than OM1 values. Organic matter contents vary with elevation in organic as well as in organomineral soils. Values of OM1 are higher at

Table 6.6 Chemical properties of the organic layers

Layer	Statist.	OM1	OM2	OM2: OM1	pH1	pH2	Ca	Mg	Na	K	Bases	Acd1	Acd2	CEC1	CEC2	BS1	BS2	P
Oi	*n*	12	12	12	9	9	13	13	13	13	13	12	9	11	8	11	8	9
	Range	6.7–55.2	23–100	1.1–4	4–5.2	3.5–3.8	0–2.1	0.1–0.8	0.2–1.1	0.1–1.3	0.7–3.3	29–185	1.6–9.0	30.7–186.7	3.2–10.7	1–7	16–67	0–7
	Mean	33.3	72.6	2.5	4.6	3.6	0.42	0.34	0.47	0.4	1.63	68.6	3.1	72.5	5	2.9	42.5	1.48
	SD	16.5	28.4	0.92	0.41	0.13	0.53	0.21	0.28	0.32	0.77	44.3	2.3	45.8	2.3	2.1	15.1	2.81
	CV (%)	49.5	39.1	36.8	8.9	3.6	126.2	61.7	59.6	80.0	47.2	64.6	74.2	63.2	46.0	72.4	35.5	189.8
Oe	*n*	13	15	11	13	13	14	14	14	14	15	16	8	14	8	14	8	12
	Range	12.1–45.7	20.2–99.1	1.1–5.7	3.2–5.3	3.2–5.2	0–3.4	0–2.1	0.2–1.1	0–1.6	0.6–7.4	19–136	0.6–5.2	21.2–141.3	2.4–8.2	1–15	16–79	0–24
	Mean	27.8	82.2	2.9	4.2	3.8	1.03	0.56	0.61	0.65	2.9	65	3.2	69.3	5.1	5.1	37.4	6.0
	SD	10.7	26.9	1.3	0.65	0.74	1.1	0.58	0.29	0.53	2.11	32.2	1.46	34.5	2.1	4.5	19.7	8.8
	CV (%)	38.5	32.7	44.8	15.4	19.5	106.7	103.6	47.5	81.5	72.7	49.5	45.3	49.7	41.2	88.2	52.6	146.7
Oa	*n*	7	10	5	8	8	10	10	10	10	10	10	5	10	5	10	5	9
	Range	3.4–30.9	15.2–92.7	2.9–27.1	3.2–5.0	3–4.7	0–2.1	0–0.7	0.2–1.1	0–0.3	0.5–3.4	16.5–117	2.6–10.2	19.9–118.3	3.1–11.5	3–17	9–29	0–18
	Mean	19.6	68.3	8.7	4.3	3.9	0.63	0.2	0.44	0.12	1.39	53.0	5.64	54.4	6.7	5.0	16.4	4.9
	SD	11.1	28.6	10.3	0.5	0.69	0.77	0.23	0.3	0.1	0.95	30.3	2.92	30	3.1	2.22	7.8	5.5
	CV (%)	56.6	41.8	118.4	11.6	17.7	122.2	115	68.2	83.3	68.3	57.2	51.7	55.1	46.3	44.4	47.5	112.4

OM1: % organic matter by Walkley–Black; OM2: % organic matter by loss on ignition (105–400°C); pH1: pH measured at field moisture; pH2: pH measured in 0.1 M $CaCl_2$;Ca, Mg, Na, K: exchangeable cations by neutral 1 N ammonium acetate; Acd1: acidity determined with trietanolamine; Acd2: acidity determined with KCl; CEC1: cation exchange capacity by sum of cations; CEC2: effective cation exchange capacity from KCl values; BS1: % base saturation from CEC1; BS2: % base saturation from CEC2; P: phosphorus in mg kg^{-1} using the Olsen method; exchangeable cations, total bases, acidity, and cation exchange capacity in cmol(+) kg^{-1}

Table 6.7 Chemical properties of the organomineral horizons

Horizon	Statist.	OM1	OM2	OM2:OM1	pH1	pH2	Ca	Mg	Na	K	Bases	Acd1	Acd2	CEC1	CEC2	BS1	BS2	P
A	*n*	8	7	7	8	8	7	7	7	7	7	7	7	7	7	7	7	7
	Range	1.2–30.9	2.9–28.7	0.47–1.2	3.4–5.0	3.1–4	0.1–0.7	0–0.1	0.2–0.7	0.1–0.4	0.6–1.5	16–110	1.2–9.8	16.7–111	2.2–10.8	1–7	9–54	–
	Mean	12.2	11.6	0.76	3.9	3.5	0.27	0.04	0.51	0.19	1.0	52.4	3.8	53.4	4.8	2.9	30.3	0
	SD	8.9	9.5	0.27	0.57	0.29	0.23	0.05	0.19	0.11	0.33	38.8	3.3	38.9	3.2	2.5	20.3	–
	CV (%)	72.9		81.9	14.6	8.3	85.2	125	37.3	57.9	33.0	74.0	86.8	72.8	66.6	86.2	66.9	–
C	*n*	7	5	–	8	8	10	10	10	10	10	10	3	10	3	7	6	4
	Range	0.34–8.6	2.2–57.3	–	3.4–5.5	3.1–4.6	0–0.3	0–0.1	0.07–0.6	0–0.1	0.07–0.1	0.2–35	1.4–4.2	0.27–36	2–4.6	1–7	3–30	0–4
	Mean	3.7	19.9	–	4.8	4.0	0.11	0.01	0.23	0.04	0.37	13.7	3.0	14.1	3.7	2.83	15.7	1.0
	SD	3.4	19.7	–	0.71	0.49	0.13	0.03	0.18	0.05	0.31	12.5	–	12.8	–	2.2	10.2	2.0
	CV (%)	91.9	98.9	–	14.8	12.3	118.2	300	78.3	125	97.8	91.2	–	9.1	–	77.7	64.5	200.0

OM1: % organic matter by Walkley–Black; OM2: % organic matter by loss on ignition (105–400°C); pH1: pH measured at field moisture; pH2: pH measured in 0.1 M $CaCl_2$; Ca, Mg, Na, K: exchangeable cations by neutral 1 N ammonium acetate; Acd1: acidity determined with trietanolamine; Acd2: acidity determined with KCl; CEC1: cation exchange capacity by sum of cations; CEC2: effective cation exchange capacity from KCl values; BS1: % base saturation from CEC1; BS2: % base saturation from CEC2; P: phosphorus in mg kg^{-1} using the Olsen method; exchangeable cations, total bases, acidity, and cation exchange capacity in cmol(+) kg^{-1}

Table 6.8 Variability of the chemical properties in the organic layers

Statistics	OM1	OM2	OM2:OM1	pH1	pH2	Ca	Mg	Na	K	Bases	Acd1	Acd2	CEC1	CEC2	BS1	BS2	P
n	30	32	28	30	30	37	37	37	37	37	38	22	35	21	35	20	29
Range	3.4–55.2	15.2–100	1.1–27.1	3.2–5.3	3.1–5.2	0–3.4	0–2.1	0.2–1.1	0–1.6	0.5–7.4	16.5–185	0.6–10.2	19.9–186.7	2.4–11.5	1.0–17.0	9.0–79.0	0–24.0
Mean	28.1	74.3	3.8	4.3	3.7	0.71	0.38	0.52	0.42	2.0	63	3.7	66.1	5.4	4	33.4	4.3
SD	13.8	27.7	4.6	0.57	0.6	0.87	0.42	0.29	0.43	1.6	35.6	2.3	36.9	2.4	4	18.3	6.8
CV (%)	49.1	37.3	121.1	12.3	16.2	122.5	110.5	55.7	104.8	80.0	56.5	62.2	55.8	44.4	100.0	54.8	158.1

OM1: % organic matter by Walkley–Black; OM2: % organic matter by loss on ignition (105–400°C); pH1: pH measured at field moisture; pH2: pH measured in 0.1 M $CaCl_2$; Ca, Mg, Na, K: exchangeable cations by neutral 1 N ammonium acetate; Acd1: acidity determined with trietanolamine; Acd2: acidity determined with KCl; CEC1: cation exchange capacity by sum of cations; CEC2: effective cation exchange capacity from KCl values; BS1: % base saturation from CEC1; BS2: % base saturation from CEC2; P: phosphorus in mg kg^{-1} using the Olsen method; exchangeable cations, total bases, acidity, and cation exchange capacity in cmol(+) kg^{-1}

Table 6.9 Variability of the chemical properties in the organomineral horizons

Statistics	OM1	OM2	pH1	pH2	Ca	Mg	Na	K	Bases	Acd1	Acd2	CEC1	CEC2	BS1	BS2	P
n	14	14	16	16	18	18	18	19	18	18	10	18	10	15	13	4
Range	0.34–30.9	2.2–57.3	3.4–5.5	3.1–4.6	0–0.7	0–0.1	0.07–0.7	0–0.4	0.07–1	0.2–45.8	1.2–9.8	0.27–111	2–10.8	1.0–7.0	3.0–54.0	0–4
Mean	8.5	15	4.5	3.8	0.17	0.02	0.35	0.09	0.36	16.6	3.5	31.2	4.5	2.8	24.5	1.0
SD	7.6	14.3	0.78	0.48	0.19	0.04	0.24	0.1	0.44	31.5	2.8	31.8	2.7	2.2	17.1	2.0
CV (%)	89.4	95.3	17.3	12.6	111.7	200.0	68.6	111.1	122.2	189.8	80.0	101.9	60.0	78.6	69.8	200.0

OM1: % organic matter by Walkley–Black; OM2: % organic matter by loss on ignition (105–400°C); pH1: pH measured at field moisture; pH2: pH measured in 0.1 M $CaCl_2$; Ca, Mg, Na, K: exchangeable cations by neutral 1 N ammonium acetate; Acd1: acidity determined with trietanolamine; Acd2: acidity determined with KCl; CEC1: cation exchange capacity by sum of cations; CEC2: effective cation exchange capacity from KCl values; BS1: % base saturation from CEC1; BS2: % base saturation from CEC2; P: phosphorus in mg kg^{-1} using the Olsen method; exchangeable cations, total bases, acidity, and cation exchange capacity in cmol(+) kg^{-1}

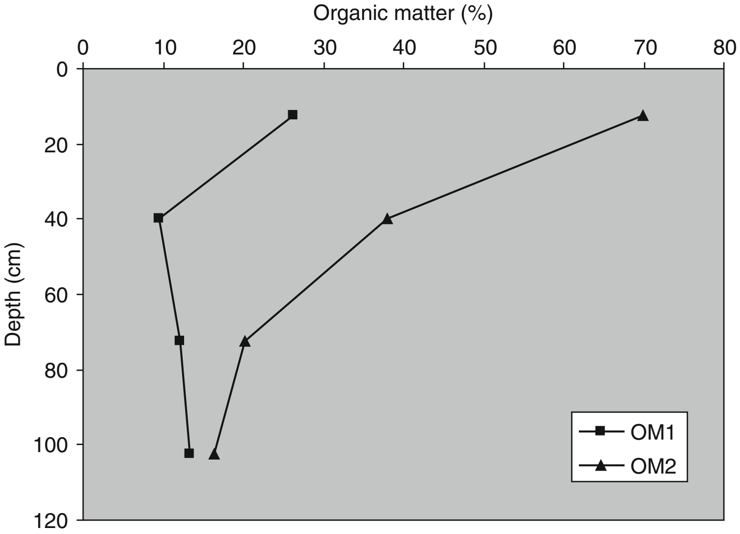


Fig. 6.10 Variation of organic matter with depth in a full organic peatsoil (P5) on sandstone. OM1 determined by Walkley–Black and OM2 by loss on ignition

650–1,800 m a.s.l. (14–55%) than above 1,800 m a.s.l. (6–26%). This trend can be explained by the higher soil temperature at lower elevation that increases the mineralization rate of organic materials in the less anoxic surface layers.

Leaves that accumulate at the soil surface constitute a large proportion of the folic layers (Oo). Temporary aeration of the topsoil during the short dry season in January–March promotes fairly rapid decomposition of this surface litter. Roots and wooden plant fragments such as branches and stems from bushes and shrubs are the main constituents of subsurface and deeper organic tiers. They decompose slowly under anaerobic conditions because of high lignin content and high C:N ratio. They are the most important source of carbon for peat formation.

In organomineral soils, organic matter contents of the A and C horizons are significantly lower than those of peat layers (Tables 6.7 and 6.9). OM1 and OM2 values are alike in A horizons (around 12% on average) except in the uppermost topsoil (Fig. 6.11), while OM2 values are several times higher than OM1 values in the C horizons (20% vs. 3%, respectively). In the mineral and organomineral horizons, organic matter is strongly mineralized and transformed into humic substances. The OM2:OM1 ratio in the A horizons varies between 0.5 and 1.2 (average 0.76). Values equal to or lower than 1 indicate higher degree of organic matter decomposition and humification. The two methods used for organic carbon determination generate similar results when dealing with organic materials evolving in better drained conditions and with higher mineralization rate.

On the basis of organic material and organic matter contents, the peat profiles can be clustered into three groups:

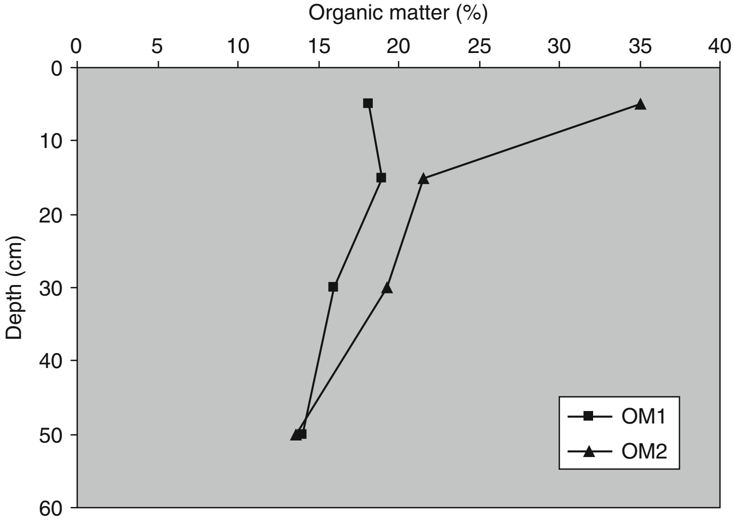


Fig. 6.11 Variation of organic matter with depth in an organomineral peatsoil (P9) on sandstone. OM1 determined by Walkley–Black and OM2 by loss on ignition

- Group A: soils having 40 cm or more organic material within 80 cm of the soil surface, and an average of more than 80% organic matter by loss on ignition (profiles P8, P12, P16, P17, P18, and P19). In most profiles, the organic material overlies the rock substratum.
- Group B: soils having 40 cm or more organic material within 80 cm of the soil surface, and an average of less than 80% organic matter (profiles P2, P5, P6, P9, P11, and P20). In general, an unconsolidated mineral layer of variable origin (weathering, colluvial, or alluvial products) is found between the organic material and the underlying bedrock. In a few cases, the organic layers overlie directly the rock substratum.
- Group C: soils having less than 40 cm organic material (profiles P1, P7, P10, and P13). Thin organic layers overlie alluvium, colluvium, or weathered rock.

6.4.2 *Soil Reaction and Acidity*

All organic soils in the Guayana Highlands are very acid. The pH values measured at field moisture (pH1) and in $CaCl_2$ solution (pH2) vary from ultra acid (pH 3.1–3.5) to strongly acid (pH 5.2–5.3). Values of pH1 and pH2 are closely correlated ($r = 0.57$). There are no significant differences between pH1 and pH2 values in both organic layers and mineral horizons. On average, pH1 values are higher by 0.2–1.4 units than pH2 values in surface layers, but differences are minimal in subsurface layers. In a few soils (e.g., P8 and P19), the opposite occurs.

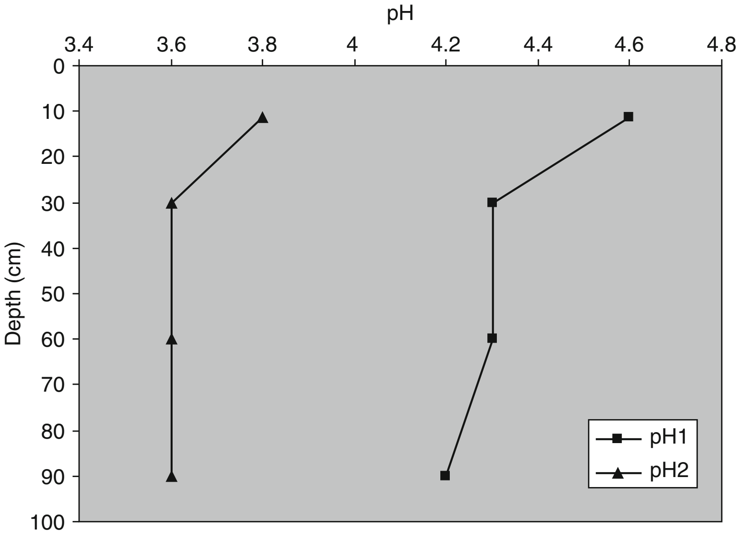


Fig. 6.12 Variation of soil reaction with depth in peatsoil P17 on sandstone. Values of pH1 measured at field moisture and pH2 in $CaCl_2$

In most soils, pH1 and pH2 values decrease gradually with depth or sometimes do not vary substantially, while increasing in the deeper mineral horizons (Fig. 6.12). Increases of 0.2–0.6 pH units were recorded in subsurface organic layers around 35–60 cm depth. In most soils, Oi layers have higher pH values than Oe and Oa layers and show more significant differences between pH1 and pH2 probably because of lesser organic matter decomposition and lower content of H^+. Generally speaking, pH is the least variable property of the organic layers. Electric conductivity determined on a few profiles (P19 and P20) was very low (0.1 dS m^{-1} on average).

Exchangeable acidity is strong in peatsoils. Both total acidity (Acd1) and salt-replaceable acidity (Acd2) show high variability within and among soils. Total acidity is 3–43 times greater than the active salt-replaceable acidity. In general, total acidity decreases with soil depth from Oi to Oa layers (from 69 to 53 cmol(+) kg^{-1}), while salt-replaceable acidity increases from Oi to Oa layers (from 3.1 to 5.6 cmol(+) kg^{-1}) (Table 6.6). Topsoils including Oi layers, shallow Oe layers, and A horizons have the lowest values of salt-replaceable acidity (3.1–3.8 cmol(+) kg^{-1}). In some soils, the decrease in total acidity with depth is related to the inclusion of mineral matter, while in others the decrease occurs in layers with similar organic matter content. In some cases, total acidity changes little with depth in profiles with high organic matter content (P17 and P19) or with organic matter decrease (P5 and P13). Higher total acidity in most of the less decomposed surface layers indicates that decomposition does not increase the density of functional groups; in most cases, a decrease occurs with greater decomposition of the organic material.

Total acidity is closely related to the content of organic matter by Walkley–Black ($r = 0.48$), but not so to the organic matter content by loss on ignition ($r = 0.24$). A large proportion of the organic matter is not chemically active at the low pH of these soils. High values of total acidity are related to the pH-dependent surface charge of the humus substances, with H^+ ions strongly tied up in the carboxyl and hydroxyl functional groups which behave as weak acids. Entrained Fe^{3+} and Al^{3+} ions or hydroxy-Al and -Fe ions are responsible for the weak-acid behavior of the organic matter (Coleman and Thomas 1967).

The salt-replaceable acidity could be associated with the presence of carboxyl groups behaving as strong acids in layers with low pH. The pH at field moisture is often 4.2 or less in layers where the salt-replaceable acidity is mostly composed of H^+ or layers that have very high organic matter content. Al^{3+} is a significant part of the salt-replaceable acidity in some layers relatively high in mineral matter, as well as in some layers with very high organic matter content. Al^{3+} saturation changes with soil depth, decreasing from Oi (12%) to Oe layers (6%) and strongly increasing in the Oa layers (43%). Also A horizons have fairly high exchangeable Al^{3+} (35%). Mineral content and exchangeable Al^{3+} show moderate-to-high correlation ($r = 0.59$). Salt-replaceable acidity and age of the organic layers are moderately related ($r = 0.45$), although variations in this relationship among profiles with similar organic matter contents suggest that factors other than age may be more important.

6.4.3 Cation Exchange Capacity and Exchangeable Cations

The cation exchange capacity (CEC) of the peatsoils is highly variable between layers (Table 6.6) and among profiles (Table A.5 in Appendix). The cation exchange capacity by sum of bases plus total acidity (CEC1) ranges between 20 and 187 cmol(+) kg^{-1}, with an average of 66 cmol(+) kg^{-1}. Mean values of CEC1 are 73, 69, and 54 cmol(+) kg^{-1} for Oi, Oe, and Oa layers, respectively, with coefficients of variation ranging between 50 and 63%. The effective cation exchange capacity determined by the sum of bases plus salt-replaceable acidity (CEC2) varies between 2 and 12 cmol(+) kg^{-1}, with an average of 5 cmol(+) kg^{-1}. Mean values of CEC2 are 5, 5, and 7 cmol(+) kg^{-1} for Oi, Oe, and Oa layers, respectively, with coefficients of variation ranging between 41 and 46%. In most profiles, CEC1, CEC2, and total acidity decrease with soil depth (Fig. 6.13). As the total bases are higher in the upper layers, their decrease with depth is more pronounced than the decrease of salt-replaceable acidity. Soils with similar organic matter contents differ significantly in CEC values. In some cases, soils with lower organic matter contents have higher CEC1 and CEC2 values than those with higher organic matter contents. Kamprath and Welch (1962) report cation exchange capacity values at pH 7 for soil organic matter to vary between 62 and 279 cmol(+) kg^{-1} and relate these considerable fluctuations to the stage of

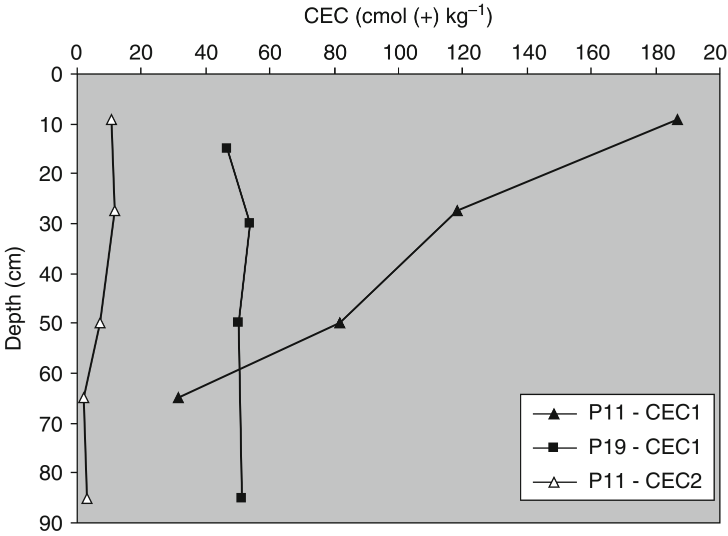


Fig. 6.13 Variation of cation exchange capacity with depth in peatsoils on sandstone (P11) and granite (P19). CEC1 determined by sum of cations and CEC2 from KCl

decomposition of the organic residues and differences in the original source of the organic materials.

In most organic soils, the relationship between cation exchange capacity and organic matter content by Walkley–Black is stronger for CEC1 ($r = 0.59$) than for CEC2 ($r = 0.31$). The relationship between CEC and organic matter content by ignition is in general weak ($r = 0.25$), indicating that the easily oxidizable organic matter is a better estimator of the cation exchange capacity in these soils. Exchangeable bases and effective cation exchange capacity (CEC2) are low in these very acid organic soils. Only strongly ionized sites are involved in the exchange reactions. The much higher values of CEC1 include weakly ionized sites which are inactive in acid soils.

In the organomineral soils, the values of CEC1 and CEC2 are significantly lower and vary from 0.3 to 111 cmol(+) kg^{-1} and from 2 to 11 cmol(+) kg^{-1}, respectively (Table 6.7). Commonly, CEC values decrease with soil depth. However, in cases where organomineral layers overlie organic layers (e.g., Oe layers), CEC increases as a response to higher contents of organic matter (Table A.5 in Appendix).

Levels of exchangeable bases are low in general, but highly variable among and within soil profiles, with coefficients of variation above 100% in the case of Ca and Mg (Table 6.6). For most soils, Ca and Na are the least scarce bases. For all organic layers together, the relative abundance of exchangeable bases is approximately $Ca^{+2} > Na^{+1} > K^{+1} > Mg^{+2}$, with average levels of 0.71, 0.52, 0.42, and 0.38 cmol(+) kg^{-1}, respectively. Exchangeable bases are mainly stored in the surface layers through nutrient cycling, while often reaching trace values in deeper layers (Fig. 6.14). This pattern is common in peats on sandstone, while peats on

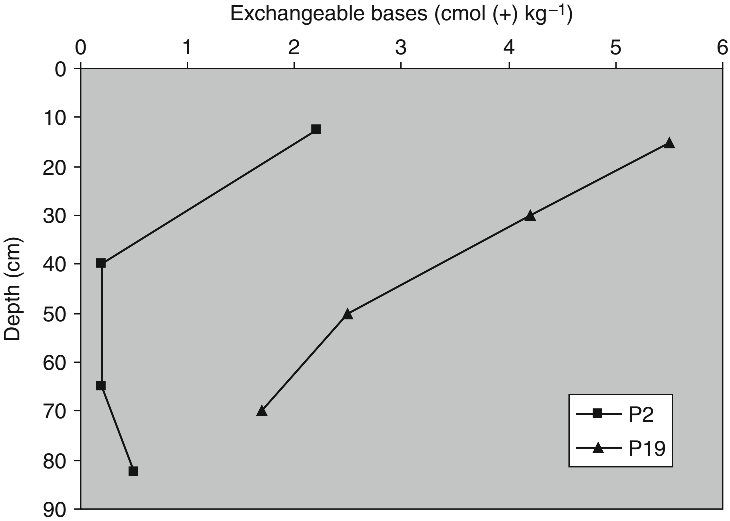


Fig. 6.14 Variation of the sum of exchangeable bases with depth in peatsoils on sandstone (P2) and granite (P19)

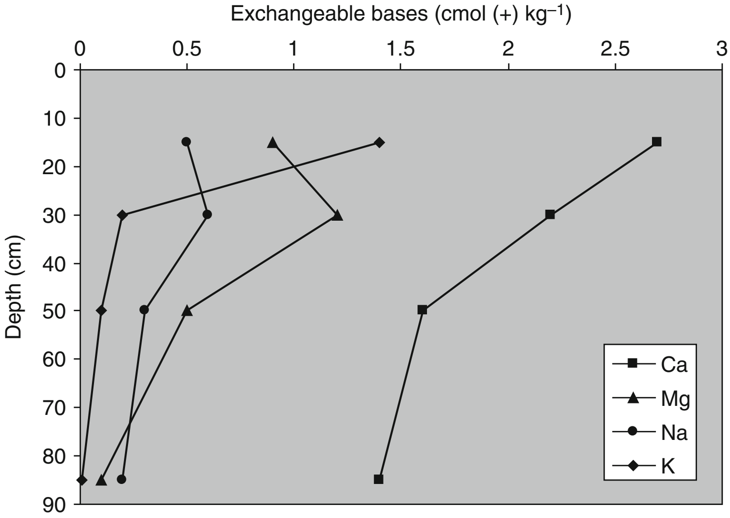


Fig. 6.15 Variation of exchangeable bases with depth in peatsoil P19 on granite

granite show a slight increase in exchangeable bases in the layers close to the rock weathering front rich in base-bearing minerals. Average values of the four macroelements Ca, Mg, Na, and K increase from Oi to Oe layers, but decrease substantially in the Oa layers (Table 6.6 and Fig. 6.15). Exchangeable K and Mg are the cations with the lowest levels of saturation in the deeper organic layers

Table 6.10 Exchangeable base saturation (%) in organic and organomineral layers

Layers	Ca^{2+}	Mg^{2+}	Na^{1+}	K^{1+}	Sum of bases
Oi	8.0	6.8	9.4	8.0	32
Oe	20.2	10.9	11.9	12.7	56
Oa	9.4	2.9	6.6	1.8	21
A	5.6	0.8	10.6	3.9	21
Organic layers	13.1	7.0	9.6	7.7	37

(Table 6.10). As exchangeable cations in organic soils can form complexes with organic compounds, they are likely to remain in the soil. However, monovalent (Na and K) and divalent (Ca and Mg) cations are less strongly adsorbed than trivalent ones (i.e., Al); thus they can be lixiviated from the soil through water runoff, percolation, or lateral movement. Exchangeable bases are significantly lower in organomineral horizons than in organic layers. Average contents of Ca, Mg, Na, and K are 0.27, 0.04, 0.51, and 0.19 cmol(+) kg^{-1} in A horizons, and 0.11, 0.01, 0.23, and 0.04 cmol(+) kg^{-1} in C horizons (Table 6.7).

Values of base saturation depend on the method used for determination of the cation exchange capacity. In the organic soils, average values of BS1 (from CEC1) and BS2 (from CEC2) are 4 and 33%, respectively. The BS2 values decrease by about 61% from the surface Oi layers to the bottom Oa layers. The BS1 values increase slightly from Oi to Oe layers but remain similar between the Oe and Oa layers (Table 6.6). Organic soils on granitic rocks have higher base saturation than soils formed on sandstones. Base saturation by sum of cations (BS1) and pH by $CaCl_2$ (pH2) are strongly correlated ($r = 0.66$). Ca, Mg, and total bases have low to moderate positive relationship with the pH at field conditions (pH1), with $r = 0.33$, 0.41 and 0.33, respectively. In the organomineral soils, average values of BS1 do not vary significantly between the A horizons and the sandy, highly dystrophic C horizons, while the BS2 values decrease by about 48% (Table 6.7).

6.4.4 *Nutrient Status and Dynamics*

Guayana Highland peatsoils have formed under waterlogged and nutrient-deficient conditions with limited organic matter decomposition. They evolve in a pluvial environment where the main sources of nutrients during the minerotrophic stage are rainfall and a tiny provision of minerals from sandstones, granites, and very locally from intrusive basic rocks (diabases). During the ombrotrophic stage, these nutrients are fixed by the vegetation successions, then released and incorporated into the peat material during biomass decomposition, and finally recycled again by the vegetation.

During peat evolution, most of the nutrients are washed out by runoff, deep percolation, seasonal fluctuation of the water table, and lateral water movement. The intensity of nutrient depletion depends on the nature and permeability of the bedrock, sandstones being more permeable than granitic rocks. Although organic materials have high total exchange capacity, the effective cation exchange capacity is low at the very acid pH of these soils. Only the strongly acid functional groups of the organic matter dissociate. High acidity is a consequence of the environmental conditions in which these organic soils evolve.

The presence of a thick surficial root mat in the Oo layers and shallower portions thereof in some Oi and Oe layers is an important feature for nutrient cycling in the Guayana peats. The concentration of exchangeable bases in the topsoil (0–30 cm) indicates that nutrient transfer and recycling occur within the upper peat layers, where organic matter decomposition increases temporarily, releasing nutrients during the short dry season. In a similar manner, Jackson et al. (2008) show that the activity of bacterial enzymes associated with carbon, phosphorus, and nitrogen cycling is highest at the peat surface and declines markedly with depth.

Conventional methods for determining available phosphorus are of limited use in acid organic soils under native vegetation, where organic phosphorus compounds are relevant. Phosphorus was determined using the Bray–Kurtz1 method for P19 and P20 and the Olsen method for the other soils. In general, available phosphorus is low, often no more than traces (Tables 6.6 and 6.7). Only a few layers in the upper 40 cm of profiles P19 and P20 have moderate levels of available P (Table A.5 in Appendix). Phosphorus is related to the organic matter content by ignition ($r = 0.40$) and to total acidity ($r = 0.65$), reflecting the relationship between available P and the functional groups of the organic compounds. These results are consistent with the findings of Andriesse (1988), who states that oligotrophic tropical peats in pristine conditions have usually very low phosphorus contents and that the net primary productivity of most natural peatlands, particularly freshwater wetlands, is limited by P deficiency.

6.5 Spatial Variations

6.5.1 Relationships with Landscape Position

Data obtained from transects at several locations show differences in peatland length, width, and depth (Table 6.11; see also Figs. 4.17–4.21 and Fig. 4.24). In general, peatland configuration is elongated. The average length-to-width ratio is 3.5:1, but can be as large as 14:1. The length of peat areas varies from 140 to 325 m, while the width ranges from 10 to 50 m. Peat areas are longest in the Maigualida massif (280–325 m) compared to 140–166 m in the other study areas. Length and width are controlled by factors such as rock hardness, joints and fractures of the bedrock, intensity of rock weathering, and (pseudo-)karst formation.

Thickness of the organic deposits varies among and within peatland areas (Table 6.12). A maximum thickness of 170 cm was observed in the Maigualida massif, with mean values of 60 cm on longitudinal transects and 113 cm on

Table 6.11 Morphometric variations of peatlands

Area	Lithology	Slope (%)	Transect	Peat length (m)	Peat width (m)	Peat depth (cm)
Cuao massif (C)	Sandstones	0.3–1	CL-1	166	20–45	20–90
			CT-1	–	28	25–120
			CT-2	–	50	40–80
			CT-3	–	30	10–50
Sipapo massif (S)	Granitic rocks	0.5–1	SL-1	140	10–40	5–90
			ST-1	–	10–15	10–50
			ST-2	–	40	30–95
		3–5	ST-3	–	38–40	15–70
Maigualida massif (M)	Granitic rocks	3–5	ML-1	325	50	30–170
		3–16	ML-2	280	30–50	10–40
		2–3	MT-1	–	50	50–140

L longitudinal transect, *T* transversal transect

Table 6.12 Thickness variability of the organic deposits (cm)

Area	Lithology	Statistics	Longitudinal transect	Transversal transect
Cuao massif	Sandstones	Total transects	1	3
		N° observations	14	9
		Range	20–90	10–120
		Mean	53.6	48.9
		SD	22.1	33.8
		CV (%)	41.2	69.1
Sipapo massif	Granitic rocks	Total transects	1	3
		N° observations	14	18
		Range	5–90	10–95
		Mean	53.6	47.6
		SD	22.1	23.5
		CV (%)	41.2	49.4
Maigualida massif	Granitic rocks	Total transects	2	1
		N° observations	62	9
		Range	10–170	50–140
		Mean	60.1	113.3
		SD	38.7	29.2
		CV (%)	64.4	25.8

transversal transects. In the Cuao-Sipapo massif, the mean depth to bedrock is 74 cm and the range is 45–150 cm, with no significant differences in peat thickness between longitudinal and transversal transects.

Soils developed on stepped slopes, colluvial fans, small floodplains, and narrow valleys are mixtures of organic and mineral layers (sand, silt loam, and silty clay loam). Mineral layers, often of allochthonous origin, occur at variable depth (13–70 cm) and with variable thickness (3–100 cm). Surficial organomineral horizons up to 20 cm thick occur locally. In (pseudo-)karstic depressions, sandy basal layers originate from rock weathering.

The lower content of roots in some A horizons, in comparison to Oi and Oe layers, indicates that a large proportion of the dead roots has been mineralized. This occurs in soils on landforms with better drainage conditions such as colluvial glacis and alveoli on stepped terrains.

There is good correlation ($r = 0.58$) between elevation and thickness of the moderately to strongly decomposed Oe and Oa organic layers. This shows the effect of elevation on temperature and evaporation, which control water surplus, and the influence of these environmental factors on the rate of accumulation and decomposition of the organic materials.

6.5.2 Relationships with Rock Substratum

Hues of 10YR and 2.5Y are the dominant colors in the soil matrix. However, soils on granite show reddish hues of 5YR and 7.5YR in the Oi and Oe layers, which could be related to the presence of iron oxides resulting from the weathering of the granitic rocks.

Root contents in the surface layers of organic soils formed on sloping landforms (karstic and pseudokarstic alveoli and colluvial glacis) are larger on granitic rocks than on sandstones (Table 6.13). Lower root content in peats on sandstones could be related to this mineralogically poorer and more permeable substratum and sandy basal layers, where nutrient depletion is favored by better drainage in sloping conditions. Vegetation differences could be an additional factor affecting the volume of roots in the surface layers.

Dry matter contents in organic soils on sandstones are larger (almost twice as much) than those of organic soils on granitic rocks, resulting in lower field water contents in the former than in the latter (Table 6.13). This could be related to higher proportions of sand, accounted as a part of the dry matter content, resulting from

Table 6.13 Variability of physical properties in peats on sandstones and granitic rocks

Bedrock	Statistics	Roots (%)	Dry matter (%)	Bulk density at field moisture (Mg m^{-3})	Bulk density of dry sample (Mg m^{-3})	Mineral content (%)	Field water content (%)
Sandstones	*n*	11	23	17	3	22	24
	Range	1.2–14.2	5.3–48.7	0.54–0.76	0.11–0.24	0–84.8	106–1,782
	Mean	6.6	18.0	0.63	0.19	37.5	790
	CV (%)	75.8	64.4	11.1	–	84.8	58
Granitic rocks	*n*	9	12	6	3	12	12
	Range	1.6–16.8	1.9–15.6	0.48–0.78	0.10–0.23	0.60–26	542–5,229
	Mean	9.1	7.2	0.60	0.15	8.23	2,081
	CV (%)	59.3	61.2	15.0	–	81.4	80

Table 6.14 Variability of % base saturation in peats on sandstones and granitic rocks

Bedrock	Ca^{2+}	Mg^{2+}	Na^{1+}	K^{1+}	Sum bases
Sandstones	7.4	5.4	9.3	5.9	28
Granitic rocks	24.4	10.5	9.9	11.4	56

weathering of the sandstones and admixture of colluvial materials. Also peats on aggradational surfaces such as narrow floodplains and glacis with large mineral contents occur mainly in sandstone areas.

Values of pH at field conditions are slightly higher in organic soils on granitic rocks (4.0–5.3) than in organic soils on sandstones (3.2–5.2). The ranges are 3.2–5.2 and 3.0–3.8, respectively, for the pH values determined with $CaCl_2$. Average levels of exchangeable Mg, K, and total bases in peats on granitic rocks are about twice as high as those in peats on sandstones, with Ca being even three times higher but no difference in Na (Table 6.14). The highest levels of exchangeable bases, total bases, and pH were obtained in peatsoils on granite in the Maigualida massif. These variations could be related to (1) lower lixiviation of bases and nutrients on massive granitic substratum, which constraints the water flow through the soil, (2) higher provision of cations from weathering of the substratum together with the inflow of cations from surrounding areas, and (3) local differences in the chemical composition of the granitic rocks, which could affect the uptake of nutrients by the vegetation and their accumulation in the plant tissues during the minerotrophic stage of peat formation, with residual effect in the ombrotrophic stage.

In conclusion, spatial variations in peatsoils are related to a set of factors that may interact at specific sites, including type and dynamics of the landforms, drainage conditions of the peatland, permeability and mineralogy of the rock substratum, age and history of the organic deposits, and type and composition of the vegetation cover, among others.

6.6 Taxonomic Classification

The soils of the Guayana Highlands are poorly to very poorly drained. They have layers composed of organic soil material of variable thickness overlying layers of mineral soil material or hard bedrock including sandstones and granites. The average content of organic carbon varies from nearly pure peat material to borderline to mineral soil material (i.e., 12% organic carbon if the mineral fraction contains no clay; up to 18% organic carbon if the mineral fraction contains 60% or more clay). Most organic soil materials in the study area contain little clay (CVG 1991).

The soils of the study area were classified according to the Soil Taxonomy (Soil Survey Staff 2006) and the World Reference Base for Soil Resources or WRB (FAO 2006), following the criteria used for the definition of organic and mineral soil materials by both systems. Table 6.15 shows the classification of the organic

Table 6.15 Classification of the organic soils

Profile	USDA classification (2006)	WRB classification (2006)
P2	Lithic Haplosaprist	Endoleptic Rheic Sapric Histosol (Hyperdystric)
P5	Lithic *Terric* Haplofibrist	Rheic Fibric Histosol (Hyperdystric)
P6	Lithic Haplofibrist	Endoleptic Rheic Fibric Histosol (Hyperdystric)
P8	Lithic Haplohemist	Endoleptic Rheic Hemic Histosol (Hyperdystric)
P9	Lithic *Terric* Haplofibrist	Rheic Fibric Histosol (Hyperdystric)
P11	Lithic *Terric* Haplosaprist	Ombric Sapric Histosol (Hyperdystric)
P12	Lithic Haplosaprist	Endoleptic Ombric Hemic Histosol (Hyperdystric)
P16	Lithic Haplohemist	Epileptic Ombric Hemic Histosol (Hyperdystric)
P17	Typic Haplosaprist	Ombric Hemic Histosol (Hyperdystric, *Thaptosapric*)
P18	Lithic Haplohemist	Epileptic Rheic Fibric Histosol (Hyperdystric)
P19	Typic Haplosaprist	Ombric Sapric Histosol (Hyperdystric)
P20	Lithic Haplosaprist	Epileptic Rheic Sapric Histosol (Hyperdystric)

Proposed: *Terric, Thaptosapric*

soils in the study area. All organic soil profiles support the requirements of the Histosol order in both classification systems (Jiménez 1995). Complementary morphological properties of the organic layers such as color and unrubbed fiber content used in the Soil Taxonomy (Soil Survey Staff 1999) were evaluated.

6.6.1 Organic Soils

6.6.1.1 Classification According to the Soil Taxonomy System

The Soil Taxonomy provides two alternatives for organic soils to be classified as Histosols: (1) the soils are saturated for 30 days or more per year in normal years, have organic soil material within 40 cm of the soil surface, and have a total thickness of either 60 cm if the bulk density moist is less than 0.1 Mg m^{-3} or 40 cm if the bulk density is higher; and (2) organic soil materials constitute two thirds or more of the total thickness of the soil to a densic, lithic, or paralithic contact, and have no mineral horizons or have mineral horizons with a total thickness of 10 cm or less. Alternative (1) is applicable to all organic soils of the study area, with profile P9 that has 12.5% organic carbon at 10–20 cm depth being a borderline case.

The suborder level in the Soil Taxonomy is defined by the degree of decomposition of the organic soil material, which is determined by the amount of rubbed fiber and pyrophosphate color in the organic part of the subsurface tier (usually 60–120 cm) or in the combined thickness of the organic parts of the surface and subsurface tiers if a mineral layer 40 cm or more thick has its upper boundary within the subsurface tier. Field determination of the degree of decomposition of the organic soil material was considered decisive, as the pyrophosphate measurement was not performed. Rubbed fiber was determined on selected layers of a few soils only. The transportation, storage, and interaction with quartz sand may have decreased the rubbed fiber content. On the basis of these criteria, most soils classify as Saprists. However, the field water content in many layers is very high when the mineral matter is low. The decomposed organic matter seems to float in water and is not compacted with age. Soil P17 is a borderline case; although the 40–80 cm layer was described in the field as moderately decomposed, the soil is placed with the Saprists because the rubbed and unrubbed fiber content is very low and the color is black. Soils P8, P16, and P18 classify as Hemists. They have relatively high field water contents and the bulk density is below 0.1 Mg m^{-3} in moderately decomposed layers of very high organic matter content. Soils P5, P6, and P9 classify as Fibrist. The latter has a slightly decomposed organic layer at 60–115 cm depth, underlying a very young mineral soil layer with relatively high organic matter content.

All the soils classified belong to the Haplo-great groups because they lack features such as a sulfuric horizon, sulfidic materials, or a cryic temperature regime, among others. At the subgroup level, most soils are Lithic extragrades because they have a lithic contact within the control section (0–130 cm), except soils P17 and P19 that classify as Typic Haplosaprists. We propose the creation of Lithic Terric subgroups to fit the soils P5, P9, and P11 because they have mineral soil layers 30 cm or more thick within the control section. In the Soil Taxonomy system, Terric subgroups key out after Lithic, and so far both criteria have not been used together, probably because Lithic Haplohemists and Lithic Haplosaprists occupy small extents in the United States, and the Lithic Haplofibrists are not known to occur there (Soil Survey Staff 1999).

At the family level, the particle-size and mineralogy classes are required for the terric layers. Histosols without terric layers do not use mineralogy classes unless the soils have ferrihumic or limnic materials. With the information available, the terric layers are labeled as sandy siliceous in P5 and P11, and as loamy siliceous in P9. Reaction classes are used for all Histosol families based upon the pH in 0.01 M $CaCl_2$ determined on undried soil. All soils evaluated by this procedure are dysic ($pH < 4.5$), except P19 and P20, which are euic because the pH in 0.01 M $CaCl_2$ is equal to or greater than 4.5 in one or more organic layers within the control section. P19 and P20 have formed on granitic rock and have a higher total base content, relatively low total acidity, and higher base saturation than peats high in organic matter on sandstone. It is probable that most of the strong acidic functional groups of the organic matter in these two soils are occupied by exchangeable bases. The soil temperature regime is approximated from elevation and temperature data recorded under bare soil in Venezuela by Comerma and Sánchez (1980). In organic soils saturated mostly with rainwater and under natural vegetation, the soil temperature is lower than the values obtained on bare mineral soils. On the basis of these considerations, an isomesic soil temperature is proposed for P2, P5, and probably P19, isohyperthermic for P16, and isothermic for the remaining soils. In addition, soils P16, P18, and P20 belong to the shallow soil depth class because they have a root-limiting layer between 18 and 50 cm.

Figures 6.16–6.18 show three representative peatsoils with fibric (P6), hemic (P8), and sapric (P2) materials as main profile components, respectively.

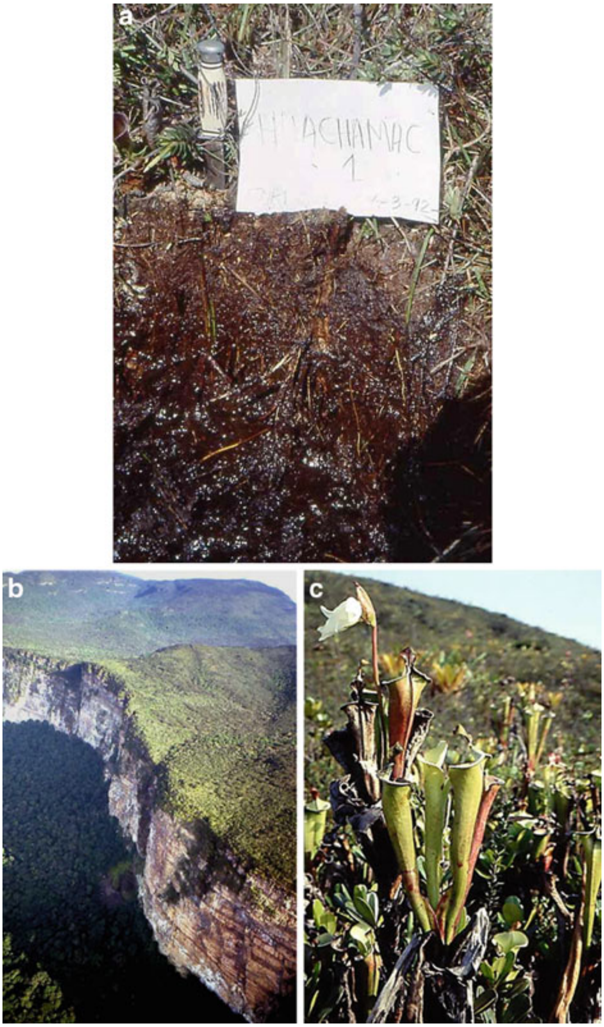


Fig. 6.16 (**a**) FIBRIC PEATSOIL on a sandstone tepui at 1,770 m a.s.l. in the Huachamakari massif. The soil is a 60 cm deep, slightly over moderately decomposed Lithic Haplofibrist with ^{14}C age 1,080 BP in the lower tier (45–60 cm) (Profile 6). (**b**) Shows a gently undulating sandstone meseta covered by shrubby meadow vegetation where the peatsoil of (**a**) is located. *Heliamphora* is a typical component of the tepui meadow (**c**) (photos Zinck)

6.6.1.2 Classification According to the WRB Framework

In the first tier of categorical detail in the WRB classification framework, the Histosol reference soil group presents two alternatives as follows: (1) organic material 10 cm or more thick starting at the soil surface and immediately overlying

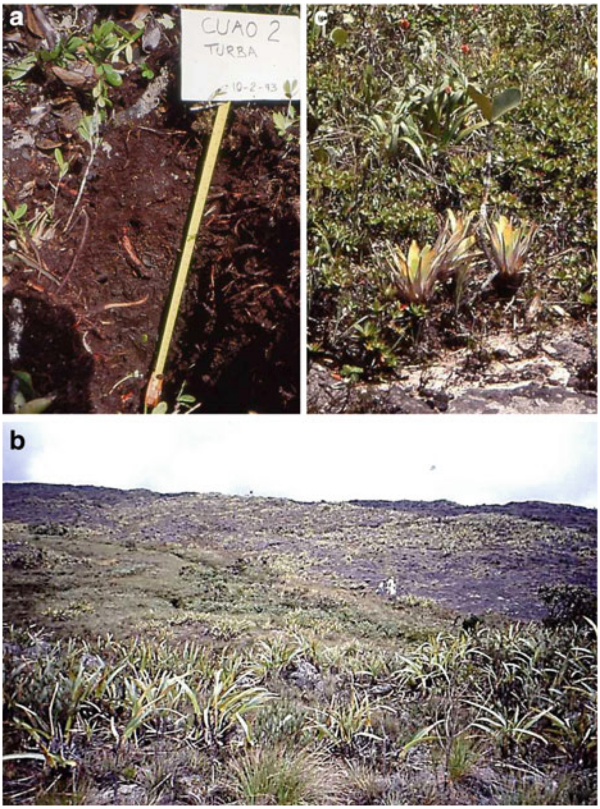


Fig. 6.17 (**a**) HEMIC PEATSOIL on a sandstone meseta at 1,800 m a.s.l. in the Cuao-Sipapo massif. The soil is a 87 cm deep, moderately to strongly decomposed Lithic Haplohemist with ^{14}C age 1,665 BP in the middle tier (30–55 cm) and 3,415 BP in the lower tier (55–87 cm) (Profile 8). The summit area in (**b**) shows a mosaic of rock outcrops and small karstic depressions covered by shrubby meadow vegetation where the peatsoil of (**a**) is located. Typical plants of the meadow cover in (**c**) include *Brocchinia, Kunhardtia* and *Stegolepis* (photos Zinck)

continuous rock; and (2) organic material cumulatively within 100 cm of the soil surface either 60 cm or more thick if 75% (by volume) or more of the material consists of moss fibers or 40 cm or more thick and starting within 40 cm of the soil surface. Alternative (2) is applicable to all organic soils, and P9 is not a borderline case in the WRB classification framework.

At the second tier of categorical detail, the Histosol reference soil group is characterized by prefix qualifiers that refer to associate and intergrade attributes, and by less important suffix qualifiers that are written between brackets. The degree of fiber decomposition is not specified for the subsurface layer (below 30 cm) as it is for deep Histosols in the Soil Taxonomy; consequently, the less decomposed surface layers often determine the selection of the appropriate prefix. Field decomposition of the organic material is used in the WRB classification framework,

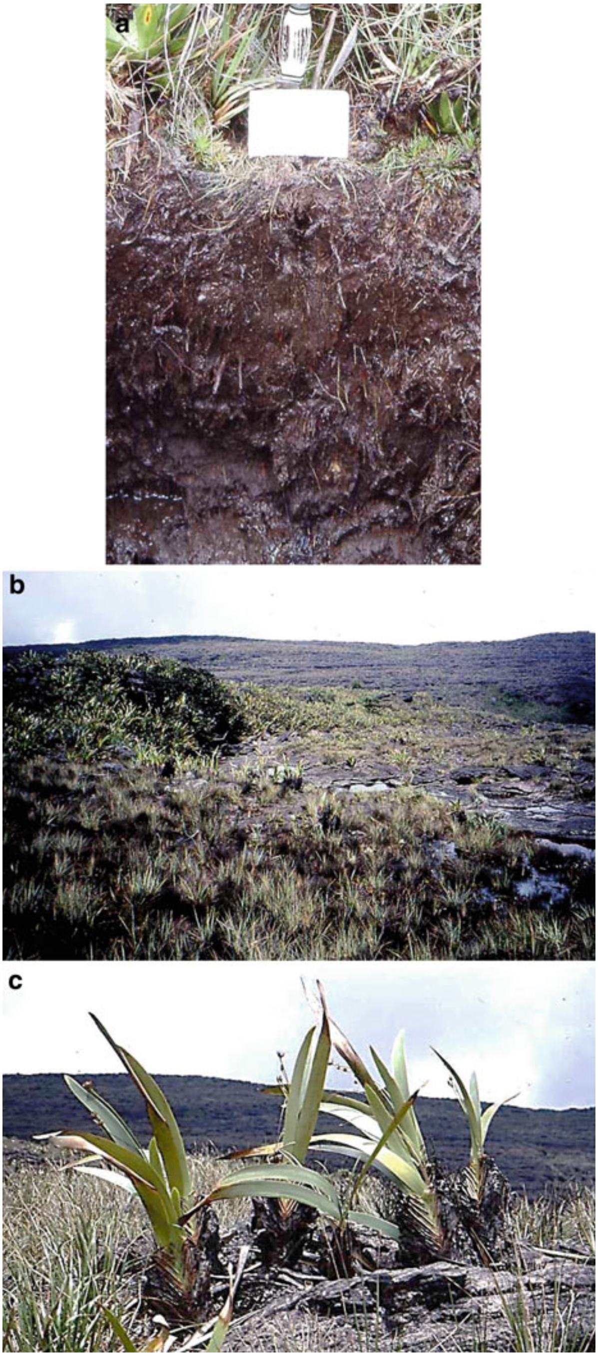


Fig. 6.18 (**a**) SAPRIC PEATSOIL on a sandstone tepui summit at 2,580 m a.s.l. in the Marahuaka massif. The soil is a 95 cm deep, strongly decomposed Lithic Haplosaprist with ^{14}C age 5,880 BP in the middle tier (20–60 cm) and 7,490 BP in the lower tier (70–95 cm) (Profile 2). (**b**) Shows a gently undulating plateau summit where the peatsoil of (**a**) has formed in a karstic depression (center of the picture) surrounded by rock outcrops. Meadow cover dominated by *Everardia* and *Stegolepis* (**c**) (photos Zinck)

because no laboratory criteria are provided for the determination of fiber content (FAO 2006). The fibric prefix indicates that an average of more than two thirds of the volume of organic material to a depth of 1 m is fiber after rubbing. In sapric material, the rubbed fiber averages less than one sixth of the volume, and hemic material is intermediate. Endoleptic means that the soil rests on continuous rock starting between 50 and 100 cm from the soil surface, and epileptic means that the soil lies on continuous rock within 50 cm. Ombric means that the Histosol is saturated predominantly with rainwater, and rheic means that the saturation is mostly with groundwater or flowing surface water. All soils are Hyperdystric at the suffix level, which means that the base saturation (by 1 M NH_4OAc) is less than 50% between 20 and 100 cm from the soil surface, and less than 20% in some layer within 100 cm of the soil surface. The Thaptosapric suffix indicates that the soil has a buried sapric layer, which is about 4,000 years older in this specific case than the overlying hemic layer.

6.6.2 Organomineral Soils

Table 6.16 shows the classification of the organomineral soils in the study area. They comprise a set of soils that do not fulfill the thickness requirements of the organic soils. They have a thin surface layer of organic soil material that is usually less than 20 cm thick. They occur in association with the Histosols and classify as Inceptisols and Entisols (Soil Survey Staff 2006), and Gleysols and Fluvisols (FAO 2006).

Applying the rules of the Soil Taxonomy, soil P1 lacks diagnostic horizons except a surface ochric horizon, which does not meet the minimum thickness of 20 cm required to fit the histic epipedon. This soil is affected by endosaturation and classifies as Typic Endoaquent, fine-silty, siliceous, semiactive, acid, and isomesic, assuming a clay content of 27–35% as inferred from the silty clay loam textural class (Fig. 6.19). Soils P7 and P13 have histic epipedons, which, together with the aquic moisture regime, determine their classification as Aquepts at the suborder level and as Humaquepts at the great group level. Soil P7 meets the requirements of an umbric horizon until the underlying rock at 70 cm. It has an irregular decrease of organic matter with depth and classifies as Cumulic Humaquept, coarse-loamy, siliceous, superactive, acid, and isothermic. Soil P13 classifies as Typic Humaquept,

Table 6.16 Classification of the organomineral soils

Profile	USDA classification (2006)	WRB classification (2006)
P1	Typic Endoaquent	*Endoleptic* Gleysol (Hyperhumic, Hyperdystric, Episiltic)
P7	Cumulic Humaquept	Histic *Endoleptic* Fluvisol (Hyperdystric)
P13	Typic Humaquept	Histic *Epileptic* Fluvisol (Hyperdystric, Epiarenic)

Proposed: *Endoleptic, Epileptic*

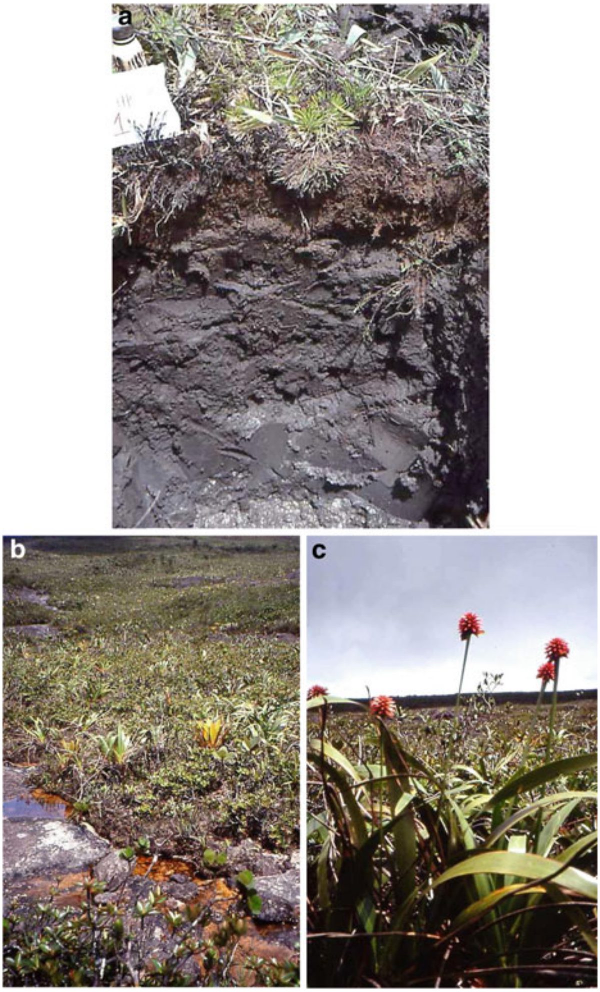


Fig. 6.19 (**a**) ORGANOMINERAL SOIL on a sandstone plateau at 2,570 m a.s.l. in the Marahuaka massif. The soil is a 60 cm deep, poorly drained Typic Endoaquent that shows a fibric surface root mat atop a colluvio-alluvial deposit containing allochthonous organic material with ^{14}C age 7,100 BP in the bottom layer (40–60 cm) (Profile 1). Narrow floodplains are frequent on tepui summits with small creeks running on bare rock and draining excess water from peatlands. Creeks also collect, transport and redeposit mineral debris provided by the weathering of rock outcrops surrounding the peatlands. The composite organomineral profile shown in (**a**) is located in the floodplain of (**b**). Mixed vegetation cover includes herbs and grasses. *Stegolepis* is a typical component (**c**) (photos Zinck)

sandy, siliceous, acid, isothermic, and shallow; the latter due to a root-limiting layer within 50 cm depth.

According to the WRB classification framework, soils P7 and P13 classify as Fluvisols because they have fluvic material characterized by stratification or by an organic carbon content decreasing irregularly with depth. The prefixes reflect the presence of a histic horizon and the depth to continuous rock. The suffixes show low base saturation and the presence of sandy layers close to the surface. Soil P1 classifies as Endoleptic Gleysoil due to reducing conditions, the lack of diagnostic horizons, and depth to continuous rock between 50 and 100 cm. The suffixes indicate high organic matter content, low base saturation, and silty texture in the upper 50 cm of the soil profile.

6.7 Conclusions

6.7.1 Morphological Features

- Guayana Highland peats show a fragmented distribution pattern and are located on specific topographic sites provided with regular water supply that ensures they are permanently waterlogged. Peatlands are generally small because of strong geostructural control. Organic and organomineral soils are associated in space, both resting on lithic substratum (mainly sandstone or granitic rocks) that commonly occurs at less than 150 cm depth. Surrounding stony and rocky terrains are locally covered by sandy colluvial mantles.
- Organic layers, including folic Oo, fibric Oi, hemic Oe, and sapric Oa, were recognized using field criteria such as color, amount of roots and other plant residues, and degree of decomposition of the organic materials. Variations in layer arrangement are largely controlled by profile position on the landscape. Peatsoils on (pseudo-)karstic landforms show commonly an Oo–Oi–Oe layer sequence. Some soil profiles exhibit Oi–Oe or, more locally, Oi–Oe–Oa sequences resting on sandy or rocky substratum.
- The thickness of the soil profiles above the lithic substratum, including organic and mineral materials, varies from 40 to 150 cm. The Oi layers are 25 cm thick on average and lie usually at the soil surface, but may also occur buried. The Oe layers are 23 cm thick on average and start at 3–60 cm depth from the soil surface. The Oa layers are 45 cm thick on average. They start at 15–110 cm depth from the soil surface and extend to 80–150 cm depth in some profiles. In general, Oa layers are the deepest organic materials in the layer sequence, close to the bedrock or to sandy C horizons. Some profiles have umbric A horizons, 28–40 cm thick and starting at 0–20 cm depth from the soil surface. At some locations, the organic tier overlies sandy or finer-textured C horizons that start at 13–85 cm depth from the soil surface. The thickness of the C horizons is 29 cm on average, but varies from 2 to 107 cm. Underlying the mineral C horizons is the bedrock, starting at 40–150 cm depth from the soil surface.
- In general, root content decreases with soil depth. There is no clear difference in average root content between Oi and Oe layers, but the amount of roots drops substantially in the Oa layers, being about 60% lower than in the overlying

layers. The presence of thick surface root mats in the Oo and upper portion of the Oi and Oe layers may result from waterlogging and oligotrophic conditions of the surface organic tier. This dense carpet of organic litter is an important feature of the Guayana Highland peats, indicating that nutrient cycling basically takes place in the upper leaf and fibrous litter layers (Oo and Oi layers).

- There are slight color differences between organic layers. The color value tends to decrease from top to bottom of the soil profiles. The Oi layers vary between dark gray and very dark brown, although black layers can occur at the soil surface. In the Oe and Oa layers, the dominant colors are black and very dark brown. Hues of 10YR and 2.5Y are most common in the soil matrix. Reddish hues (5YR and 7.5YR) occur in Oi and Oe layers of soils formed on granodiorite, reflecting the effect of iron oxides that result from the weathering of the mafic rock minerals.
- Peats are soft and unconsolidated deposits and are water-saturated the largest part of the year. The water table is usually near or above the ground surface. Water surplus due to high rainfall and low evapotranspiration, low hydraulic conductivity, water retention by the organic materials, and sloping topography contribute to the concentration, accumulation, and ponding of surface water in depressions giving rise to peat bogs.

6.7.2 Physical Properties

- Dry matter content increases with depth from 35 to 47% in Oi layers and from 43 to 87% in Oe layers. Also in the A horizons, relatively better drained, dry matter content increases especially toward the underlying C horizons. Pore space and field water content decrease markedly with increasing mineral matter.
- In general, unrubbed and rubbed fibers decrease with soil depth, indicating that physical fiber decomposition is weak in the surface peat layers, but increases with depth close to the mineral C horizon or the lithic contact. Rubbed fiber amounts to about 16% in both Oi and Oe layers, but only 7% in Oa layers. Fiber determination strongly depends on the strength of the laboratory treatment applied and the presence of sand grains in the organic layers that contribute to the breakdown of fibers during the treatments.
- Mineral matter content in organic layers is highly variable, ranging from nothing to about 80%. The average mineral content decreases first slightly from Oi (29%) to Oe (26%) layers and then increases in the Oa layers (31%). Variations in mineral content are mostly related to the geomorphic processes that favored the accumulation of mineral matter in low-lying landscape positions, together with the accumulation and preservation of the organic residues.
- Wet bulk density is the physical parameter with lowest variability. In most soils, bulk density at field conditions slightly increases with depth in the organic layers, while in some others it decreases in deeper layers. Wet bulk density values range from 0.54 to 0.78 Mg m^{-3}, without significant differences between organic layer types. Dry bulk density varies with depth from 0.11 to 0.16 to

0.20 Mg m^{-3} in Oi, Oe, and Oa layers, respectively. The low bulk density of the peat materials is related to the high pore space occupied by water. The permanently waterlogged layers are only slightly compacted with depth. In contrast, in many tropical lowland peats, bulk density is higher in the surface than subsurface layers because of more advanced organic matter decomposition.

- Average values of field water content are 1,026, 1,170, and 1,532% for Oi, Oe, and Oa layers, respectively. This physical parameter is highly variable among individual organic layers and whole profiles, with extreme values of 106 and 5,229%.

6.7.3 Chemical Properties

- The Guayana Highland peatsoils vary markedly in organic matter content from nearly pure organic material to layers borderline to mineral soils. Average organic matter content is 74% by loss on ignition and 28% using the Walkley–Black method. In general, organic matter contents decrease with peat depth. Changes in organic matter content are often more related to the mixture of organic and mineral materials along the profiles than to the degree of decomposition of the organic materials. Peat materials vary spatially, with amounts of organic matter higher than 90% at some sites, and according to elevation with the highest amounts of organic matter occurring at 650–1,800 m a.s.l. In organomineral soils, organic matter contents of the A and C horizons are significantly lower than in peat materials.
- Soil pH is the least variable chemical property of the organic layers. The pH values vary from ultra acid (pH 3.1–3.5) to strongly acid (pH 5.2–5.3). The pH at field moisture is usually higher than the pH in $CaCl_2$ solution. The Oi layers have higher pH values than the other organic layer types. In most soils, lower pH values are associated with increase in organic matter because the latter is a source of H^+ ions and contributes to soil acidification. Total acidity is around 3–43 times higher than salt-replaceable acidity, which indicates the high pH-dependent surface charge of the organic compounds.
- The cation exchange capacity (CEC) of the peatsoils is very variable among profiles and between layers. The cation exchange capacity by sum of bases plus total acidity ranges between 20 and 187 cmol(+) kg^{-1}, with an average of 66 cmol(+) kg^{-1}. The effective cation exchange capacity determined by the sum of bases plus salt-replaceable acidity varies between 2 and 12 cmol(+) kg^{-1}, with an average of 5 cmol(+) kg^{-1}. Although organic materials have high total exchange capacity, the effective cation exchange capacity is low at the very acid pH of these soils. In most profiles, acidity decreases with soil depth.
- Levels of exchangeable bases are low in general, but highly variable among and within soil profiles. For all organic layers together, the relative abundance of exchangeable bases is $Ca^{+2} > Na^{+1} > K^{+1} > Mg^{+2}$, with average levels of

0.71, 0.52, 0.42, and 0.38 cmol(+) kg^{-1}, respectively. Exchangeable bases are mainly stored in the surface layers through nutrient cycling, while often reaching trace values in deeper layers. Base saturation by sum of cations and by $CaCl_2$ is 4 and 33%, respectively. Organic soils on granitic rocks have higher base saturation than those formed on sandstones.

- Peatsoils have formed under waterlogged and nutrient-deficient conditions with limited organic matter decomposition. During the minerotrophic stage, the main sources of nutrients are rainfall and a tiny provision of minerals from bedrocks. During the ombrotrophic stage, some of these nutrients are fixed by the vegetation successions, then released and incorporated into the peat material during biomass decomposition, and finally recycled again by the vegetation. Most of the nutrients are washed out by runoff and deep percolation. However, the concentration of exchangeable bases in the topsoil (0–30 cm) indicates that nutrient transfer and recycling occur within the upper peat layers, where organic matter decomposition increases temporarily, releasing nutrients during the short dry season. In general, available phosphorus is low, often no more than traces.

6.7.4 Soil Variability

- Spatial variations in peatsoils are related to a set of factors that may interact at specific sites, including type and dynamics of the landforms, drainage conditions of the peatland, permeability and mineralogy of the rock substratum, age and history of the organic deposits, and type and composition of the vegetation cover, among others. In general terms, landscape position and the nature of the bedrock mainly control the spatial variations of peats and peatlands.
- In general, peatland configuration is elongated. The average length-to-width ratio is 3.5:1, but can be as large as 14:1. The length of peat areas varies from 140 to 325 m, while the width ranges from 10 to 50 m. Thickness of the organic deposits varies among and within peatland areas. A maximum thickness of 170 cm was observed, but the most common range is 45–150 cm.
- Peats formed on sandstones and on granitic rocks, respectively, differ in several aspects including color, root content, dry matter content, pH, and available macronutrients, among others. Peats are slightly redder on granitic rocks than on sandstones. Root contents in the surface organic layers are larger on granitic rocks than on sandstones, the latter being a mineralogically poorer and more permeable substratum. Dry matter contents in organic soils on sandstones are larger (almost twice as much) than those of organic soils on granitic rocks, resulting in lower field water content in the former than in the latter. Average levels of exchangeable bases in peats on granitic rocks are almost twice as high as those in peats on sandstones, with Ca being even three times higher.

6.7.5 Soil Classification

- Soils were classified according to the Soil Taxonomy and the World Reference Base for Soil Resources (WRB), following the criteria used for the definition of organic and mineral soil materials by both systems. All organic soil profiles support the requirements of the Histosol order in both classification systems.
- At the suborder level of the Soil Taxonomy, most soils classify as Saprists (50%), followed by Hemists (25%), and Fibrists (25%), on the basis of the degree of decomposition of the organic soil material. All soils belong to the Haplo-great groups and most soils are Lithic extragrades because they have a lithic contact within the control section (0–130 cm).
- According to the WRB framework, the organic soils classify as Sapric, Hemic, and Fibric Histosols in equal proportions. Rheic Histosols are more frequent (60%) than Ombric Histosols (40%). All soils are hyperdystric.
- The organomineral soils classify as Endoaquents and Humaquepts according to the Soil Taxonomy, and as Gleysols and Fluvisols according to the WRB framework.

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