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**The soils of
RAINFOR Project**

C. A. Quesada et al.

Soils of amazonia with particular reference to the rainfor sites

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Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

The tropical forests of Amazonia occur on a wide variety of different soil types reflecting a rich diversity of geologic and geomorphologic conditions. We here review the existing literature about the main soil groups of Amazonia, describing their genesis, geographical patterns and principal chemical, physical and morphologic characteristics. Original data is also presented with profiles of exchangeable cations, carbon and particle size fraction illustrated for the principal soil types, also emphasizing the high diversity existing within the main soil groups when possible. Maps of geographic distribution of soils occurring under forest vegetation are also introduced, and to contextualize soils into an evolutionary framework, a scheme of soil development is proposed having as its basis a chemical weathering index. We identify a continuum of soil evolution in Amazonia with soil properties varying predictably along this pedogenetic gradient.

1 Introduction

1.1 Soil diversity in Amazonia

Tropical soils can arise from an extremely wide variety of parent materials, climatic conditions, biotic interactions, landforms, geomorphic elements and soil age. Many of these factors vary more widely in the tropics than in the temperate zone (Sanchez, 1976; Richter and Babbar, 1991). Amazonia itself comprises a vast and heterogeneous region, with many of these factors, especially parent materials; landforms, geology and geomorphologic history varying widely (Sombroek, 1966, 2000; Irion, 1978). On the other hand, factors such as soil temperature and soil moisture regimes are common to many Amazonian soils (Sanchez, 1976; van Wambeke, 1978). In the early days of soil science in Amazonia, Marbut and Manifold (1926) observed at least six different groups of soils occurring commonly in the region and suggested that many soils occurring in the tropics had little or no morphological differences from those observed for

BGD

6, 3851–3921, 2009

The soils of RAINFOR Project

C. A. Quesada et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**The soils of
RAINFOR Project**C. A. Quesada et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

temperate zone soils. Sanchez (1976) and Richter and Babbar (1991) argued against the old misconception that tropical soils are invariably ancient, lateritic and intensively weathered, demonstrating that tropical soils are very diverse, encompassing all different taxa, from the lowest to the highest pedogenetic levels. Indeed, Sanchez and Buol (1975) had by this time already found that soils previously mapped as Ferralsols in the Peruvian Amazon actually were Ultisols, Alfisols and Inceptisols (Acrisols, Luvisols/Lixisols and Cambisols in the World Reference Base soil classification system: IUSS Working Group WRB, 2006), and suggested that ancient Ferralsols may actually be confined to areas of the Guyana and Brazilian shields. Sombroek (1966) also reported a large diversity of soils in his studies of the Brazilian Amazon, describing a high diversity of “latosols”, “kaolinitic latossolic sands”, “podzols”, “lithosols”, ground water laterites, hydromorphic grey podzolics, “Regosols”, Gleysols, saline and alkali soils, Indian black earths and *terras roxas estruturadas* (equivalent to present day Nitisols) plus other minor and uncommon soil groups not properly identified.

Richter and Babbar (1991) gave an analysis of available soil surveys up to that time, comparing results from the FAO World Soil Map (1988) and the Brazilian Soil Survey for Amazonia (EMBRAPA, 1981), also giving estimated coverage areas for each different soil order. They estimated that Ferralsols covered 0.391 of Brazilian Amazonia, with Acrisols covering 0.323, Gleysols and Plinthosols 0.063 and 0.069, respectively, and with Arenosols covering 0.044, Leptosols 0.045, Podzols 0.028, and Cambisols 0.013 of the area with Fluvisols and Nitisols covering less than 0.010. They also indicated that there was a considerable bias towards the dominance of Ferralsols in the FAO map which was related to the methodology used by the FAO system; Ferralsols being mapped on the basis of estimates of climate and vegetation data instead of empirical soil analysis.

Much of the soil diversity in Amazonia has originated from the considerable differences in geology and geomorphology that occur across the area. Interestingly, much early work on this subject was actually undertaken by limnologists interested in reasons for observed variations in the elemental composition of river waters within the

Basin. Based on such observations, Fittkau (1971) divided the Amazon Basin into four regions, as shown in Fig. 1. He considered the characteristically low levels of chemical elements (especially calcium) found in the waters of the core area of Central Amazonia (Sub-region IV in Fig. 1) to reflect the already low soil fertility of this region (Aubert and Tavernier, 1972) this being associated with the lack of geological activity in recent times. In addition, it was argued that the sediments deposited in this area would also have had a very low nutrient content, such as for the sands derived from the ancient Guyana shield, which is about 1700 million years old (Fittkau et al., 1975). High topographic stability combined with continuous hot and wet weather has also already resulted in a deep weathering and leaching of parent material with lack of erosion over the generally flat topography eliminating bedrock as a source of nutrients for this part of Amazonia.

Nevertheless, Fittkau (1971) found the natural waters of his peripheral sub-regions (Northern, Western and Peripheral Amazonia in Fig. 1) to be significantly richer in chemical elements than the central Amazon Basin with the waters of Western Peripheral Amazonia being considerably enriched. Not surprisingly, these are also the areas in the Amazon Basin where relatively fertile soils occur, this particularly being the case close to the Andes where topography plays an important role in the maintenance of soil fertility through erosion of the soil surface and exposition of the underlying parent material (Jordan and Herrera, 1981).

The soils of Fittkau's Central Amazonian sub-region IV are mainly derived from rocks and sediments from the middle Tertiary with a high probability of belonging to the end of the Cretaceous and thus likely to have experienced more or less continuous weathering for more than 20 million years (Irion, 1978). Included in this sub-region, are the Cretaceous-Tertiary sediments, derived from the erosion of the Guyana and Brazilian shields, known as the Barreiras formation (Herrera et al., 1978). These ancient, pre-Cambrian Guyana and Brazilian shields, with their series of igneous and metamorphic rocks, are placed to the north and south of the lower Amazon River, encompassing Fittkau's regions I and II, respectively.

**The soils of
RAINFOR Project**

C. A. Quesada et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I◀](#)[▶I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

**The soils of
RAINFOR Project**C. A. Quesada et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Between these shields and the Amazon River (Fittkau's region IV) occur strips of Palaeozoic sediments in which Devonian shales are represented to an appreciable extent (Irion, 1978). By contrast, western Amazonian soils (Fittkau's region III) mostly consist of pre-Andine sediments from the Cretaceous-Tertiary period uplifted in the Pliocene. Thus this formation probably commenced between 1 and 2 million years ago. For instance, at the neighbourhood of Acre state, Brazil, a number of fresh water and marine sediments occur as a result of the Andean orogeny and fluctuations of the sea level during warmer climates (Irion, 1978; Kronberg et al., 1989, 1998). Also, the western Amazon region includes large areas where shallow soils on hillslopes dominate. Thus active contributions of weathering of parent material to soil fertility can be expected (Irion, 1978).

Floodplain soils of western Amazonia are also much more recent. Formed in the Pleistocene and Late Holocene flood plains those soils are not much older than 5000 years (Irion, 1978). Although Fittkau's region III has usually been considered fertile (Sanchez and Buol, 1975), soils within this region often contain extremely high exchangeable aluminium levels (Lips and Duivenvoorden, 1996). This is the consequence of the ongoing weathering of high activity aluminium bearing minerals such as hydroxyl-interlayered vermiculite (Marques et al., 2002; Lima et al., 2006).

As noted already, differences in geomorphology and soil fertility across Amazonia are reflected in the dissolved elemental compositions of the waters in the rivers draining each region (see also Herrera et al., 1978; Irion, 1984; Medina and Cuevas, 1989; Furch and Klinge, 1989; Gaillardet et al., 1997). In that respect, Amazon tributaries which originate in the Andean region are often termed "white-water rivers". These rivers are in fact brown in colour due to suspended particles eroded from mountain slopes but what is important is that they have higher levels of all nutrients compared to other Amazonian rivers, notably Ca, P and Mg (Furch and Klinge, 1989) – although concentrations are still below the average when compared to rivers draining the temperate and boreal regions (Herrera et al., 1978). Nutrient rich floodplain soils result from sediment deposition from such white-water rivers (the *Várzea*); and such soils

**The soils of
RAINFOR Project**C. A. Quesada et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

have been considered the flooded counterpart of the fertile and well-drained *terra firme* soils of western Amazonia (Furch and Klinge, 1989). Examples of white-water rivers include the Solimões, Juruá and Madeira, all of whom have their headwaters draining the Andean Cordillera with complex and varied lithologies (Gaillardet et al., 1997). In the Solimões basin the core of the Cordillera consists of a pre-Cambrian basement formed either by sediments, igneous or metamorphic rocks. Evaporites, dark shales, fractured carbonates and Mesozoic red beds are the main rocks overlying the basement. Further downstream, Tertiary fluvio-lacustrine sediments (Içá formation) dominate the lowland portions of the Solimões River (Gaillardet et al., 1997). In the Andean part of the Madeira River, the main rocks are Palaeozoic sediments associated with shales and rare Cambrian evaporites. The Juruá and the lowland portions of Madeira and Solimões Rivers drain Tertiary fluvio-lacustrine deposits (Gaillardet et al., 1997).

By contrast, waters that drain the pre-Cambrian Guiana and Brazilian shields are generally known as “black-water” rivers with the dark colour of their waters due to a high content of dissolved humic and fulvic acids in various stages of polymerization (Herrera et al., 1978; Gaillardet et al., 1997). But some tributaries that originate in the eastern and central areas of Amazonia, usually draining Ferralsols, are often “clear”, with transparent, crystalline waters (Herrera et al., 1978). Neither black nor clear water rivers carry appreciable suspended soils particle loads. They are also characterised by very low nutrient concentrations – a consequence of the low nutrient content of the substrates from which these rivers drain (Herrera et al., 1978).

The *Rio Negro* is probably the best example of an Amazonian black water river. The very low nutrient concentrations of the soils that drain into it have arisen as a result of several cycles of weathering, erosion, and sedimentation. All nutrients are found in very small amounts with [Ca] being notably low (Furch and Klinge, 1989).

This paper aims to provide an up to date review of the different soil types of the Amazon Basin, adopting the World Reference Base (WRB) approach for soil classification (IUSS Working Group WRB, 2006). Distribution maps of the main soil types occurring under forest vegetation and its respective cover area are also introduced using the

World Soil Information Database (ISRIC, 1995). As well as drawing on the earlier work of others, original data is also presented demonstrating a diversity of Amazonian soils, both within and between the various WRB soil groups.

2 Material and methods

2.1 Study sites

The soils of a total of 71 primary forest plots are used in this study, including forests in Brazil, Bolivia, Colombia, Peru, Ecuador and Venezuela. A subset of 18 soil profiles is used to exemplify soil characteristics among and within each WRB group. Details for each site are given in Table 1 of Quesada et al. (2009a).

2.2 Soil sampling and laboratory methods

Detailed descriptions of soil sampling and laboratory methods are given in Quesada et al. (2009a) but are also briefly summarised here. Exchangeable cations were determined by the silver thiourea method (Pleysier and Juo, 1980), soil carbon was determined in an automated elemental analyser as described by Pella (1990) and Nelson and Sommers (1996). Particle size analysis was undertaken using the Boyoucos method (Gee and Bauder, 1986).

For the purposes of soil classification, cation exchange capacity (CEC) and exchangeable bases were also measured by ammonium acetate pH 7 (NH₄Ac pH 7, Van Reeuwijk, 2002) on all pit samples. According to the requirements of the WRB soil classification system, CEC values were adjusted for organic matter content and expressed on clay basis. Further, although exchangeable Al had routinely being analysed using the silver thiourea method (Quesada et al., 2009a), it was also determined by the more usual 1M KCl extraction method for selected Brazilian samples (Procedures for Soil Analysis, 2002). Thus, all pit samples were analysed using the Ag-TU method, with a subset of these samples analysed by both methods.

BGD

6, 3851–3921, 2009

The soils of RAINFOR Project

C. A. Quesada et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**The soils of
RAINFOR Project**

C. A. Quesada et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



With the purpose of using exchangeable Al as an aid for soil classification using the WRB, [Al] values obtained in Ag-TU extracts were then adjusted to 1M KCl levels using an equation derived by the means of a non parametric regression. This showed two methods correlate well (Fig. 2a), but Al extracted by 1M KCl tended to be slightly lower at low concentrations and higher at high concentrations.

Exchangeable bases extracted by NH₄Ac pH 7 yielded comparable results to extractions made by the Ag-TU method (Fig. 2b), with the exception of some samples with very low concentrations which were more strongly extracted by Ag-TU. In agreement with the similarities in extraction levels of exchangeable bases and aluminium by the two methods (Fig. 2a and b), soil ECEC extracted by NH₄Ac pH 7 and Ag-TU were very similar (Fig. 3a). Nevertheless, CEC values determined by ammonium acetate pH 7 almost inevitably yielded substantially higher values than did ECEC in Ag-TU at soil pH (Fig. 3a). Again differences in extraction levels were higher at lower cation concentrations and declined with increasing concentrations. Such differences in extraction power are related to artificial charges created on the surface of variable charge colloids, which results from rising soil pH with the extracting solution (Uehara and Gilman, 1981). This differences in extraction power of CEC and ECEC results in contrasting base saturation levels (Fig. 3b) according the method used. Indeed, the calculation of base saturation by NH₄Ac pH 7 for the soils in this study almost always resulted in values less than 0.5 and in the placement of soils in the dystic category despite soils sometimes having high levels of exchangeable bases and base saturation in Ag-TU.

To investigate the weathering levels of soils within the dataset, the weathering index Total Reserve Bases (Σ_{RB}) was calculated. This index is based on total cation concentration in the soil and is considered to give a chemical estimation of weatherable minerals (Delvaux et al., 1989). Soil samples were extracted for total elemental concentrations (Ca, Mg, K and Na) by strong acid digestion using concentrate sulphuric acid followed by H₂O₂, with Σ_{RB} equal to $[Ca]_T + [Mg]_T + [K]_T + [Na]_T$, where $[X]_T$ represents the total concentration of each element in mmol_c kg⁻¹ soil.

2.3 Representation of soil profiles

To graph representative vertical profiles of exchangeable cation concentrations, [C] and soil particle size distribution, we used the equal area quadratic smoothing spline approach of Bishop et al. (1999) using a value for the smoothing parameter, λ , of 0.01 with all profile depths, z , standardised prior to the fitting of the spline according to $z^* = z/z_{\max}$ where z^* is the standardised value and z_{\max} is the maximum depth sampled. As detailed in Quesada et al. (2009a) soils were typically sampled over a series of depths viz 0.00–0.05 m, 0.05–0.10 m, 0.10–0.20 m, 0.20–0.30 m, 0.30–0.50 m, 0.50–1.00 m, 1.00–1.50 m and 1.50–2.00 m. Where physical constraints prevented sampling to 2 m depth, z_{\max} was taken as the depth at which sampling stopped and the number of horizons in the spline fitting program adjusted accordingly. Note that in all graphs presented here, cation values presented are for the Ag–TU extractions only.

2.4 Preparation of soil distribution maps

The Soil and Terrain database for Latin America and the Caribbean (SOTERLAC), version 2.0, at a scale of 1:5 000 000 (Dijkshoorn et al., 2005) was used as basis for the soils classes and its spatial distribution. Non-forest areas were excluded from the analysis using a vegetation map derived from optical and microwave remote sensing data over the Amazon basin, at 1 km spatial resolution and capable discriminating 16 land cover types and with an overall accuracy of above 0.85 (Saatchi et al., 2009). The following land cover classes were aggregated and considered as “forest”: closed terra firme forest, open/degraded terra firme forest, bamboo/mixed semi-deciduous forest, liana dominated/open forest, transitional/deciduous forest, sub-montane forest, montane forest, closed woodland, closed swamp forest, open swamp forest and mixed vegetation swamp.

The sub-division of the soil classes provided in the dataset from SOTERLAC were aggregated into the following main categories to encompass all the variability per WRB Soil Reference Group (RSG): Acrisols, Alisols, Arenosols, Cambisols, Fluvisols,

BGD

6, 3851–3921, 2009

The soils of RAINFOR Project

C. A. Quesada et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Ferralsols, Gleysols, Histosols, Leptosols, Lixisols, Nitisols Plinthosols, Podzols and Regosols. Other soils were not mapped due to their limited coverage in Amazonia these being Andosols, Solonchak, Solonetz, Phaeozems and Luvisols. A Geographic Information System (GIS) was used to compile and carry out map algebra with the reclassified soil and vegetation maps combined using Boolean operators in order to generate a final result of soil types on forested vegetation formations.

3 Results and discussion

3.1 Describing Amazonian forest soils: distribution and diversity

The distribution and coverage across each Reference Soil Group (RSG) are shown in Fig. 4. Individual maps for the principal RSG are also available as Supplementary Information <http://www.biogeosciences-discuss.net/6/3851/2009/bgd-6-3851-2009-supplement.zip>. These show that the geographic distributions of forest soils vary widely across the Amazon Basin, usually associated with large scale geomorphologic features. For example, Acrisols and Ferralsols occur mainly on the Brazilian and Guyana shields and in the sedimentary zone along the central and eastern portions of the Amazon River. Although Ferralsols are absent in western and south-western areas of Amazonia, Acrisols do occur, but are apparently limited to Tertiary fluvio-lacustrine deposits and other sedimentary formations near the Andes. Other soils occur almost exclusively in the vicinity of the Brazilian and Guyana shields such as Arenosols, Lixisols, Nitisols, Histosols and Podzols, with the later occurring in areas of the Rio Negro basin as well. Plinthosols also occur in small patches along the Brazilian and Guyana shields but are more common in sedimentary areas near the Juruá, Purus and Madeira rivers (i.e. Içá formation).

Regosols and Leptosols occur along the shields as well, but more commonly appear in the proximity to the Andean foothills, occurring however mostly outside of the Amazonian border. Floodplains and areas along the major rivers mostly account for Fluvisols

BGD

6, 3851–3921, 2009

The soils of RAINFOR Project

C. A. Quesada et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**The soils of
RAINFOR Project**C. A. Quesada et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

and Gleysols, such as the catchments of the upper Amazon tributaries and along the Amazon itself. Large Gleysol patches also occur in the Araguaia catchments in Brazil and in North Colombia, also spreading along the Andean border in sedimentary zones in the Peruvian Amazonia. Some other soils are mapped as occurring almost exclusively in the Andean foothills and adjacent sedimentary zone such as Cambisols and Alisols. Also, the proportions of soils occupying the eutric lower classification levels (Quesada et al., 2009a) are much greater in this zone. The coverage of each soil group is summarized in Table 1. Ferralsols and Acrisols alone account for 0.605 of Amazonian forest soils, with Plinthosols, Gleysols, Cambisols and Leptosols accounting for most of the remaining portion (0.087, 0.083, 0.056 and 0.054, respectively). All the remaining soils altogether cover less than 0.115 of the area. We note that the estimation of soil coverage shown is based only on soils underneath forest, and note that the area mapped is defined for a new definition of the Amazon border (Soares-Filho et al., 2006).

Accounting for the diversity of Amazonian soils, Table 1 in Quesada et al. (2009a) lists geographic coordinates, country of location and the identified soil type for the 71 sites sampled as part of that study. This shows that of the 32 RSG in the WRB classification scheme, 14 Reference Soil Groups were identified, viz. one Leptosol, five Gleysols, one Fluvisol, 13 Cambisols, one Andosol, one Nitisol, 10 Plinthosols, two Umbrisols, 10 Alisols, one Lixisol, seven Acrisols, 13 Ferralsols, two Arenosols and four Podzols. A large variation within RSG was also found, with three lower level differentiations for Alisols, two for Acrisols, seven for Cambisols, five for Ferralsols, two for Plinthosols, two for Podzols and two for Gleysols. Geographical locations of the soils (Fig. 3 of Quesada et al., 2009a) suggest our sampling to have given a reasonable representation of the soils of the Amazon basin in six different countries.

With a view to demonstrating the diversity of soils in Amazonia, each of the 14 different major Reference Soil Groups found in our study are now considered. Representative soil profile data is given for each soil group, with additional profiles given for soils showing significant variation within their RSG. As in Driessen et al. (2001), soils

are organized according to the major factors conditioning their morphological, chemical and physical properties.

3.2 Soils conditioned by limited age

3.2.1 Leptosols

5 Leptosols (some Entisols Orthents and other lithic subgroups in US Soil Taxonomy) are shallow soils over continuous rock or soils that are extremely gravelly and/or stoney. Although being azonal, leptosols tend to be found on rock outcrops and mountainous regions (Driessen et al., 2001). Here they usually occur on rocks that are resistant to weathering, where erosion has kept pace with soil formation, or where the soil surface
10 has been removed (Buol et al., 2003). They are characterized by various kinds of continuous rocks or unconsolidated material with less than 0.2 of fine earth by volume. Within the Amazon Basin often they often support short forest or savannas as in the Inselberg complexes in the frontier zone of Guyana, Brazil, Venezuela and Colombia, as well as in the Andean fringe (Sombroek, 2000; Cotler and Maass, 1999; Reatto et
15 al., 1998).

Nevertheless, the occurrence of Leptosols under forest can be seen in Fig. 5, supporting one of the highest forest biomass in our dataset, having large trees over almost bare rock. Figure 6 show the profiles of Ca, Mg, K, Na, Al and soil carbon for this Hyperskeletal Leptosol (Orthodystric) in Venezuela (ELD-34). Consistent with the suffix Orthodystric, exchangeable cations concentrations were moderately low, reflecting
20 both parent material fertility and the small degree of development of this soil. Nutrients were found only in the top soil, where organic materials accumulate. The fine earth fraction was very coarse (<0.20 as fine earth fraction), mostly due to mineral fragments which had not been broken down to a fine degree, thus granting this soil with the qualifier Hyperskeletal. The soil depth was very variable, but usually not exceeding
25 0.25 m. In terms of vertical structure, the soil had a well developed litter layer above a thin soil horizon over rock. The diabase rock from which this soil originates is resis-

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



tant to weathering and bare rock outcrops accounted for most of the ground surface, with the soil mostly appearing in concave portions of the terrain or in cracks among the rocks. The relatively high carbon content of this soil seems to reflect the accumulation of litter in the surface, as there is little opportunity for carbon to move down in the soil, being thus ultimately conditioned by the soil depth.

With the purpose of facilitate the understanding of WRB qualifiers by readers not familiar with soil classification, Table 2 lists a glossary with the meaning for the most common suffix and prefix used through the text. Complete description of each qualifier can be found at IUSS working group WRB (2006).

3.2.2 Cambisols

The Cambisol group (Inceptisols in US Soil Taxonomy) consists of soils with incipient formation. The initial stages of transformation in the soil material are evident, with developing soil structure below the surface horizon and discolorations (Driessen et al., 2001). Cambisols tend to evolve from a variety of medium and fine textured parent materials. They are also characterized by ABC profiles with slight or moderate weathering, and by the absence of appreciable quantities of clay illuviation, organic matter accumulation or readily extractible aluminium and iron compounds (IUSS Working Group WRB, 2006). Most Cambisols are soils with some horizon differentiation and are in transitional stage of development, actively developing from a young soil to a more mature form with argic, spodic or ferralic B horizons (Buol et al., 2003). The Cambisol group keys out late in the WRB taxonomy hierarchy which implies that this group may include some soils that just missed out one or more requirements for other reference groups (IUSS Working Group WRB, 2006). High quantities of weatherable minerals and the absence of any signs of advanced pedogenesis is further evidence of the early stages of the soil formation characteristic of cambisols (Sanchez, 1976; Buol et al., 2003). There are however, often evidences of initial weathering and transformation of primary minerals (Sanchez, 1976; Buol et al., 2003). The cambisols of tropical regions occur in recent geomorphic surfaces that may be erosional or aggradational (Driessen

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



et al., 2001). Given the high weathering intensity of the tropics, young alluvial deposits and fresh rocks exposed at shallow depths may evolve to cambisols in a relatively short time (Buol et al., 2003). Most cambisols in this study were found close to the Andes on erosional surfaces in western Amazonia.

5 Figure 7 shows two Cambisol profiles of contrasting fertility: A Haplic Cambisol (Alu-
mic, hyperdystric, Clayic) located at Tambopata, South Peru (TAM-05, Fig. 7a) and
a Haplic Cambisol (Orthoeutric) located in Ecuador (BOG-02, Fig. 7b). For the Peru-
vian soil, exchangeable bases were very low, declining strongly with depth, but with
exchangeable aluminium concentrations high, and increasing slightly with depth. Soil
10 carbon was higher in the soil surface due to organic matter inputs from the forest lit-
terfall, whilst as for most profiles examined as part of this study subsurface carbon
declines slowly with depth. Clay content was high, also increasing slightly with depth,
but in this case such an increase in the control section does not fulfil the requirements
for argic horizon such as is the case for Alisols, Acrisols and Lixisols (Sects. 3.3.3 to
15 3.3.5). The elevated aluminium proportion of this soil and its high clay content is what
confer the suffix descriptors Alu-mic and Clayic to its name. This soil had a maximum
depth of 1.7 m below where saprolite was present. The vertical distributions of clay and
[Al] suggest that transformations towards another soil type are currently taking place,
with this soil most likely evolving to an Alisol. Suggestive routes for soil development
20 are discussed further in Sect. 3.7.

By contrast the exchangeable bases for BOG-02 were among the highest found in
Amazonia (Fig. 7b) with very low extractable aluminium content, and cation concen-
trations varying little with depth, which granted this soil the denomination Orthoeutric.
Carbon profiles showed a strong decline in depth. Soil texture was sandy clay loam
25 to clay loam, this being considered typical for this type of soil. Soil depth was shallow,
reaching saprolite at 0.8 m and rock at 1.1 m. This soil was strongly conditioned by its
steep topography being constantly renovated by erosion.

As noted by Sombroek (1984) it is thus important to appreciate that soils in the
Cambisol group can be highly variable in terms of their fertility. This variation occurs

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I◀](#)[▶I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

because the close proximity to parent material makes Cambisols very dependant on quality of the weathering substrate. Also, varying degrees of weathering and mineral transformation are observed, adding to the variability found for these soils (Buol et al., 2003). Another source of variability in soil fertility may rise from the inclusion in this classification group of soils that just failed criteria for other groups (Wilding et al., 1983; IUSS Working Group WRB, 2006), although this did not seem to be a significant factor for this study.

3.3 Soils conditioned by a wet tropical climate

3.3.1 Plinthosols

Plinthosols (Plinthic Great Groups in US Soil Taxonomy) are soils which have as their principal characteristic the elevated concentration of plinthite, an iron rich, humus poor mixture of kaolinite clay and quartz which changes irreversibly to hard pans on exposure to repeated wet and drying cycles (Sombroek, 1984; IUSS Working Group WRB, 2006). Plinthite most commonly evolves from the weathering material of basic rocks as opposed to acidic ones and as formation of plinthite is associated with fluctuations of ground water levels these soils are thus often associated with lower landscape positions (Sombroek, 1966; Lima et al., 2006). The development of the plinthic layer depends on the accumulation of sesquioxides through removal of silica and bases under hydrolysis, following the discharge of weathering products. This results in a relative accumulation of weathering resistant materials such as sesquioxides, quartz and kaolinite (Driessen et al., 2001). Absolute accumulation of these materials is also possible through alluvial or colluvial deposition. Another mechanism for plinthite formation is the segregation of iron which occurs under alternating reduction and oxidation conditions (Sombroek, 1984). Under water saturation much of the iron is in the ferrous form and therefore mobile, this iron precipitates as ferric oxide when conditions become drier and will not, or only partially, re-dissolve when conditions become wetter again. This may explain why plinthite shows a typical distribution pattern with red mottles in platy, polyg-

BGD

6, 3851–3921, 2009

The soils of RAINFOR Project

C. A. Quesada et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



onal or reticulate configuration (Driessen et al., 2001). In its unaltered form, plinthite is firm but can be cut with a spade. If the land is later uplifted or suffers changes in its moisture cycle, however, plinthite can become irreversibly hardened to form petroplinthite.

5 Soils with plinthite layers are common under tropical forest vegetation, and soils with petroplinthite are most common in transitional zones between rainforests and savannas, but it can also occur in wetter areas where most of it would presumably have been dislocated, hardened, transported and finally deposited as alluvial or colluvial parent material. Despite Plinthosols being found, at least to some extent across the entire
10 Amazon Basin (Sombroek, 1966, 1984; Sombroek and Camargo, 1983) most of the plinthosols identified in this study were found in western Amazonia, where they commonly occur as a consequence of well defined geomorphological and/or landscape characteristics (Fritsch et al., 2006). Physical characteristics of Plinthosols are usually restrictive; the soil is very compact with high bulk density, being the soil structure being
15 generally weak in all horizons (Sombroek, 1984).

Two soil profiles have been chosen to illustrate lower level variations within the Plinthosol group. The first soil profile is a Haplic Plinthosol (Alumic, Orthodystric, Siltic) located in the Acre state, Brazil (DOI-02, Fig. 8a). For this soil Ca and Mg are relatively high at the surface in relation to other Amazonian soils, but with Ca declining sharply
20 until the depth of 0.4 m, remains relatively constant at about $10 \text{ mmol}_c \text{ kg}^{-1}$ until 1.2 m and then declines to practically zero values. Magnesium follows a different pattern, being mostly constant until 0.4 m deep and then sharply increasing until 1.2 m, after which it starts to decline to practically zero values at 1.7 m Aluminium on the other hand, is practically absent until a depth of 0.3 m, sharply increases until 0.7 m increasing again
25 below 1.2 m. This vertical distribution of cations in Plinthosols profiles seems to reflect the ongoing removal process of silica and bases (Lima et al., 2006). Carbon does not present any special pattern apart from being relatively high in the surface layer.

The second profile is for an Endostagnic Plinthosol (Alumic, Hyperdystric) located in southeastern Colombia, western Amazonia (AGP-02, Fig. 8b). This soil had a slightly

**The soils of
RAINFOR Project**C. A. Quesada et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

stronger influence of slow draining water than for DOI-02, with the presence of stagnic colour patterns in the profile, similar to that described by Fritsch et al. (2006). Even though exchangeable bases concentrations were much lower than DOI-02, the overall distribution pattern was virtually identical, but with higher aluminium concentrations throughout. Carbon content showed a similar pattern as for DOI-02 this also being the case for depth dependent variations in soil particle distribution.

3.3.2 Ferralsols

Ferralsols (Oxisols in US Soil Taxonomy) are soils that carry marks of strong weathering and desilication and typically occur in tropical, humid, free draining environments. They generally cover old geomorphic surfaces or develop over sediments that were pre-weathered from ancient regoliths (Buol et al., 2003; Buol, 2002). Ferralsols may also develop in younger materials which weather rapidly, such as basic and ultrabasic rocks and geologically old volcanic material, but these occurrences are generally of limited spatial importance (Beinroth, 1982; Buurman and Soepraptohardjo, 1980). They are commonly found on stable topography of tropical regions where wet and hot climate favour intensive weathering (Sanchez, 1976). As reported by Driessen et al. (2001), because of their extremely advanced state of pedogenic development, the weathering of the mineral fraction of Ferralsols releases only negligible amounts of nutrients or aluminium. Moreover, P adsorption capacity is high (de Mesquita Filho and Torrent, 1993) and the total P pool is usually small (Smeck, 1985). Also, no neo-formation of clay minerals is expected to occur. This mineral fraction is usually dominated by kaolinite and iron/aluminium oxides as goethite, hematite and gibbsite (Sombroek, 1984; Buol, 2002), a mineral assemblage that makes Ferralsols variable charge soils (Herbillon, 1980; Qafoku et al., 2004). Despite Ferralsols being chemically poor and with an acidic reaction, most have well developed physical conditions. In general they are deep, well drained soils which have low silt content, low bulk density, strong fine and very fine granular structure, low available water content and a high hydraulic conductivity (Sanchez, 1976; Richter and Babbar, 1991; Buol and Eswaran, 2000; Buol, 2002).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Clays do not disperse in water and there is little osmotic swelling because the cation concentration at the surface of the kaolinitic clay is low. Ferralsols also have a considerable capacity to accumulate soil organic matter due to its prevalent organo-mineral interactions and large soil depth (Dick et al., 2005; Zinn et al., 2007).

5 In this study, Ferralsols were found in central and eastern areas of Amazonia as well as in its southern border. No Ferralsols were found in the geologically younger areas close to the Andes, in agreement with the previous analysis of Sanchez and Buol (1975) who suggested that Ferralsols in Amazonia should be mostly confined to areas of the Guyana and Brazilian shields, as well as sedimentary zones between them (i.e. the Barreiras formation). As mentioned already, Ferralsols were once thought to dominate the Amazonian landscape, but this was subsequently shown to result from a low reliability of soil mapping in the area (Richter and Babbar, 1991; van Wambeke et al., 1983). For example, Sombroek (1966) suggested that the area covered by Ferralsols (especially the “Belterra clay” soils), was much larger than we now know to be the case. 10 Indeed, later in his career he reported that initial assessments were overestimated, and that the areas covered by Belterra clay in western areas of Amazonia were much more limited than he first thought.

Two Ferrasols profiles are shown, the first is a Geric Acric Ferralsol (Alumic, Hyperdystric, Arenic) situated in the Mato Grosso state, Brazil, in the southern edge of the Amazon forest zone (SIN-01, Fig. 9a). Consistent with its description as Geric, the concentration of exchangeable bases and aluminium in this Ferralsol are very low throughout the profile with the exception of the surface layer where concentrations are twice as high, most likely due to organic matter content and nutrient recycling. But aluminium increases deeper down in the profile as a result of saprolite weathering. The prefix Acric on the other hand refers to a slightly increment of clay through the profile, 20 which is in turn clearly dominated by sand. Carbon content is relatively short and mirror bases distribution, suggesting that organic matter is a major source for nutrients.

The other profile shown is a Gibbssic Geric Ferrasol (Alumic, hyperdystric, Clayic, Xanthic), located in northeastern Amazonia, Brazil (JRI-01, Fig. 9b), often called “Bel-

**The soils of
RAINFOR Project**C. A. Quesada et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

terra clay” in the soils literature (Sombroek, 1966). As opposed to the other Ferralsol, this soil has a very high clay proportion (>0.75), which may be partially responsible for its relatively high carbon content (Dick et al., 2005). Although being still at the lower fertility end of the spectrum, exchangeable bases and aluminium are almost five times higher than for SIN-01. The qualifiers Gibbsic and Xanthic included in the WRB classification refer to presence of significant amounts of the mineral gibbsite and to the inherent yellow colour common to this soil, respectively. This diversity in chemical and morphological characteristics emphasizes the high variability and diversity within RSG groups.

3.3.3 Alisols

Alisols (Ultisols in US Soil Taxonomy) are strong acid soils with high activity clays accumulating in the subsoil. They occur on parent materials which contain a substantial amount of unstable aluminium-bearing materials such as hydroxy-interlayered smectite or vermiculite. Ongoing hydrolysis of these minerals release Al which then occupies more than half of the exchangeable sites. Alisol formation is confined to environments where most of the primary minerals have disappeared, and with secondary clay minerals of high activity dominating the clay complex. They have a CEC in ammonium acetate pH 7 above $240 \text{ mmol}_c \text{ kg}^{-1}$ clay, a base saturation of less than 0.5 in a major part of the profile. They usually occur on old land surfaces with hilly or undulating topography, in humid and hot climates. In this study, Alisols were found in Ecuador, Peru and Colombia.

Two lower level variations of Alisols have their profiles shown here. The first is a Haplic Alisol (Hyperdystric, Siltic) in South Peru (TAM-06, Fig. 10a), and the second is a Hyperalic Alisol (Hyperdystric, Clayic) in Ecuador (TIP-05, Fig. 10b).

Exchangeable [Ca] and [Mg] were relatively high in the Peruvian Alisol, along with a high exchangeable [Al]. Although Ca was mostly found near the soil surface, [Mg] were relatively constant until 1.2 m, increasing steadily with depth. Most of the Al seems to be being released in the active clay illuviation zone, but with Mg weather-

BGD

6, 3851–3921, 2009

The soils of RAINFOR Project

C. A. Quesada et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



ing reaching its maximum in the zone of increased silt content. Such vertical gradients in the nature of active weathering reflect the intermediate pedogenetic status of Amazonian Alisols.

The Ecuadorian soil has a slightly different cation and particle size profile. Calcium dominates the top 0.05 m of the profile, but below that both [Mg] and [Al] increase with depth to the point where Mg (and some Ca) dominate the ECEC. Aluminium concentrations reach a maximum in the clay illuviation zone, while [Mg] and [Ca] have their increases lower down in the profile in association with an increase in coarse fraction increments. This suggests a non-uniform weathering profile as well, probably in accordance with different weathering stages for the different soil minerals with depth.

Such patterns of [Al] and [Mg] reflect the pedogenetic stage of Alisols as well as the properties of 2:1 clay minerals (Driessen et al., 2001). During the early formation of Alisols, hydrolysis and transformation of primary weatherable minerals occur in the parent material with some leaching of silica. This produces a saprolite with little weatherable primary minerals and a dominance of high activity clays, most likely formed by the transformation of micas. This is followed by a redistribution of clay in the soil and the formation of an argic horizon. It is when secondary high activity clays start to weather that Alisol formation occurs and the observed cation patterns become distinguishable. High active clays are unstable in environments that are depleted of silica and alkaline and alkaline earth cations. With their weathering they release soluble aluminium and for some parent materials, iron and magnesium from the octahedral internal layers of the 2:1 clay minerals. The process of high activity clay weathering usually overlaps with clay redistribution. Clay illuviation only occurs at pH varying from 5 to 6.5, at lower acidic pH, Al^{+3} become dominant and saturate the complex. Such Al saturation flocculates the clay and impedes further dispersion, leading to its accumulation in the profile.

Exchangeable bases in the Alisols profiles were among the highest levels found in Amazonian soils. Alisols are generally considered soils of limited fertility as they have their ECEC dominated by aluminium. But the very low fertility levels common

**The soils of
RAINFOR Project**

C. A. Quesada et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

to many Amazonian soils make them comparatively rich, occupying the more fertile end of the spectrum. Also, as is shown in Quesada et al. (2009a), phosphorus supply is also generally favourable in these soils and base cations often co-exist with the high aluminium levels. Indeed, despite the very high [Al], there is little evidence of aluminium toxicity in plants living on such soils. For example, Gama and Kiehl (1999) found that crops growing in western areas of Amazonia did not show serious Al toxicity symptoms; even though the soils they were growing on had exchangeable Al levels of approximately $145 \text{ mmol}_c \text{ kg}^{-1}$. Marques et al. (2002) explain such observations by extremely high Al levels extracted from such soils coming from adsorbed Al ions held within the structure of the 2:1 minerals such as hydroxyl-interlayered smectites, and suggest that in situ this “exchangeable” Al may not necessarily be in equilibrium with solution [Al]

The mapped distribution of Alisols (Fig. 4; see also Fig. S5 in the Supplementary Information <http://www.biogeosciences-discuss.net/6/3851/2009/bgd-6-3851-2009-supplement.zip>) suggests only a limited coverage of these soils in Amazonia. But this may not actually be the case. For instance, all Alisols found in this study were found in areas outside of those identified as such in the SOTERLAC Database. In addition, soil profiles found in the RADAMBRASIL soil survey (RADAMBRASIL, 1978), in particular in the Brazilian states of Acre and Amazonas (west and southwest part of the Brazilian Amazonia), show several soil profiles which would most likely be classified as Alisols in the WRB system. These soils named at the time as *podzólicos vermelho amarelo álico*, have high activity clays, with [Al] ranging from 50 to as much as $268 \text{ mmol}_c \text{ kg}^{-1}$ and with other characteristics fulfilling all requirements for Alisols. Furthermore, there are many other soils in that region having characteristics very similar to that of Alisols, but which most likely have been converted to WRB in the SOTERLAC database as Acrisols, because such soils were generally assumed to contain only low activity clays. However, the definition of clay activity is different between the WRB and the Brazilian Soil Classification System as was used at the time of RADAMBRASIL. While the WRB states limits for clay activity

**The soils of
RAINFOR Project**

C. A. Quesada et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



definition in a clay basis, the Brazilian System uses bulk soil CEC values (de Oliveira and van der Berg, 1996). Therefore many soils regarded as low activity clay in the RADAMBRASIL would probably have been considered as high activity clays soils if CEC had been corrected for clay content. Another problem regarding the conversion of clay activity from the Brazilian System is the lack of confirmation by standard chemical analysis (CEC above or below $240 \text{ mmol}_c \text{ kg}^{-1}$ of clay, extracted by ammonium acetate pH 7 and corrected for carbon content) because such analysis were generally lacking in the RADAMBRASIL program. As an additional concern the correlation between the Brazilian and WRB systems is generally weak with this prohibiting the accurate translation of soil map legends as needed for scientific purposes (de Oliveira and van der Berg, 1996). Taken together these observations suggest that many soils described as Acrisols in SOTERLAC for the Brazilian Amazon may, infact, be Alisols.

3.3.4 Acrisols

Acrisols (Ultisols in US Soil Taxonomy) are considered the second most common soils in Amazonia, covering an area of approximately $2.15 \times 10^6 \text{ km}^2$ (Table 1), although as mentioned in Sect. 3.3.3, this may be an overestimate. As for Alisols, these soils are characterized by accumulation of clays in a subsurface argic horizon, which can be a result of several different processes, including sedimentation, lithological discontinuities, and clay migration (West et al., 1998). They are strongly weathered acid soils with low base saturation and acid reaction (Lathwell and Grove, 1986; Richter and Babbar, 1991; West et al., 1998; Driessen et al., 2001; IUSS Working Group WRB, 2006). However, unlike Alisols, Acrisols are dominated by low activity clays with a lower CEC range ($<240 \text{ mmol}_c \text{ kg}^{-1}$ clay, extracted by ammonium acetate pH 7). They usually evolve on acid rock of Pleistocene age or older, being notably high in strongly weathered clays which are still undergoing further degradation. The sediments that form the parent material for Acrisols often have been pre-weathered for more than one weathering cycle (West et al., 1998). Nevertheless, geomorphic studies in tropical areas have invariably shown that although Acrisols occupy younger geomorphic positions than Ferralsols,

BGD

6, 3851–3921, 2009

The soils of RAINFOR Project

C. A. Quesada et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**The soils of
RAINFOR Project**C. A. Quesada et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

they also occur in older and more stable areas than those occupied by other soils with which they are often geographically associated (Beinroth et al., 1974; Lepsch and Buol, 1974; Beinroth, 1981; West et al., 1998). Contents of Al, Fe and Ti oxides are comparable to Ferralsols with their clay fraction consisting almost entirely of well crystallized kaolinite and some gibbsite (Buol et al., 2003). Nevertheless, small quantities of mica, vermiculite and smectite occur in many of these soils (Sanchez and Buol, 1974; West et al., 1998). Also, as for Ferrasols, Acrisols are often reported as having variable charge clays (Uehara and Gilman, 1981; Qafoku et al., 2004)

As reviewed by West et al. (1998) the physical properties of Acrisols (and the related Luvisols, Lixisols and Alisols) often present major constraints for plant growth. Textural variation within the profile is a common problem because of water perching, limited infiltration and thus increased runoff. Moreover, the sandy/loamy surface horizons often have weak structure which favours compaction and high bulk density. These conditions in turn result in low infiltration rates, limited rooting and seedling emergence. In many of these soils, the bulk density is greater than the bulk density considered to be limiting root proliferation due to high mechanical impedance. The presence of patches of macro porosity and localized lower bulk density may allow root penetration into horizons of overall high bulk density, but if roots are restricted to these zones the volume of soil exploited for water and nutrients must be limited.

In this study Acrisols were found in North Peru, Venezuela and Brazil and Fig. 11 shows soil profiles for a Vetic Acrisol (Hyperdystric) located at Mato Grosso state, Brazil (ALF-01). Unlike Alisols, exchangeable cation concentration in the subsoil of Acrisol are drastically lower than the surface horizon and despite soil carbon, and to some extent soil cations, experiencing a slight increase in the clay increment zone, there is little vertical variability in sub-soil nutrient concentrations, this contrasting with other soils within the same morphological group such as Alisols and Lixisols. This suggests that any contribution from active weathering of soil minerals may be small in Acrisols, also implying that such soils are more strongly weathered than Alisols and Lixisols. At the soil surface, which is predominantly sand, the higher concentration of base cations pre-

sumably arises from the recycling of organic matter. Consistent with the Vetic qualifier which predicts a cation exchange capacity below the level of $60 \text{ mmol}_c \text{ kg}^{-1}$ in some layer within the top 1 m of soil, this Acrisol CEC resulted below that level in all parts of the profile. However, despite lower cation concentrations than other soils with similar textural gradients, the ALF-01 Acrisol was twice as fertile as the Amazonian Ferralsol examples.

3.3.5 Lixisols

Lixisols (Alfisols in US Soil Taxonomy) are soils morphologically related to Acrisols, Alisols and Luvisols through the presence of argic horizons, being separated from Alisols and Luvisols by having low activity clays and low CEC. They are separated from Acrisols on the basis of their higher base saturation. For Lixisols, clay is transported from an illuvial horizon to an argic subsurface horizon that has low activity clays and moderate to high base saturation. Similar to Acrisols, they have a low CEC range ($<240 \text{ mmol}_c \text{ kg}^{-1}$ clay extracted by ammonium acetate pH 7) but unlike Acrisols, they have base saturation of 0.5 or more. They are considered soils with advanced weathering stage but due to their parent material (often limestone or mafic rocks) base saturation is still high, with soil reaction eliminating excessive amounts of Al in the soil solution (Driessen et al., 2001).

Only one Lixisol was identified in this study, a Cutanic Lixisol (Ferric, Hypereutric) in Venezuela (RIO-12) and Fig. 12 shows profiles for this soil. Exchangeable bases clearly dominate the exchange complex, with Mg and Ca occupying most of the ECEC, with K, Na and Al present in smaller quantities. Magnesium is in clear excess to Ca which may be a result of parent material chemistry or immobilization of Mg during neof ormation of secondary minerals (Thomas, 1974). The concentration of Mg increases in the clay illuviation zone, reaching its highest concentrations at the maximum clay content. Below [Al] and [K] increase slightly with a small reduction in [Mg]. The vertical distribution of elements in this soil suggests that active weathering of soil minerals may be still taking place. Although base saturation is high in Lixisols, the actual ECEC is

BGD

6, 3851–3921, 2009

The soils of RAINFOR Project

C. A. Quesada et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



relatively low, which results in this hypereutric Lixisol actually having a shorter base cation pool than the hyperdystric Alisols shown above.

This Lixisol also showed limitations in its physical structure, it was very compact, had unweathered rocks scattered throughout and heavy structure in the B horizon.

- 5 Although physical constraints are a common feature in all soils with increments in clay content, problems such as compaction, low porosity, high bulk density and top soil hardening when dry are particularly common in Lixisols (Nicou, 1974, 1975; Nicou and Charreau, 1980; IUSS Working Group WRB, 2006).

3.3.6 Nitisols

- 10 Nitisols (Ultisols and Oxisols in US Soil Taxonomy) are deep, red (Rhodic), well-drained tropical soils with a clayey nitic subsurface horizon that has typical polyhedral, blocky structure elements with shiny ped faces. Usually they evolve from the weathering of intermediate to basic parent rock, possibly rejuvenated by recent additions of volcanic ash. Their mineralogy is dominated by kaolinite and meta-halloysite, but minor amounts of illite, vermiculite and randomly interstratified clay minerals may be present along with hematite, goethite and gibbsite. These soils are iron rich soils usually found on level
15 of hilly landscapes (Driessen et al., 2001). In Brazil, these soils are known as *terras roxas estruturadas* and are often highly sought for their agricultural capabilities. Nitisols in Amazonia occupy areas where basic effusions occur (i.e. diabase and dolerite)
20 such as in outcrops of the Guyana and Brazilian shields and some carboniferous deposits (Sombroek, 1966). For example Nitisols were reported to occur along the Trans-Amazon highway, in the upper Xingu area and in the state of Rondônia (southwestern Amazonia) but these soils usually have patchy coverage only (Sombroek, 1984).

- 25 The formation of Nitisols involves an initial process of ferralization, similar to that for Ferralsols but it is at an early stage. The formation of Nitic properties follows with strong angular, shiny peds being developed in the subsurface horizon. This nitidization is apparently a result of alternating micro swelling and shrinking and produces well-defined structural elements with strong, shiny pressure faces. These soils also involve

BGD

6, 3851–3921, 2009

The soils of RAINFOR Project

C. A. Quesada et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**The soils of
RAINFOR Project**C. A. Quesada et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I◀](#)[▶I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

5 a strong biological influence, termite, ants and worm activity is thought to homogenize and create further structure and gradual diffuse horizon boundaries (Driessen et al., 2001). The cation exchange capacity of Nitisols is high compared to that of similar tropical soils such as Ferralsols, Lixisols and Acrisols. The reasons for higher fertility are the usually high clay content and relatively high levels of organic matter. Base saturation varies from 0.1 to 0.9 in most soils (Richter and Babbar, 1991). Despite that, Nitisols also show clay increment with depth although usually they have slightly better structure than those other soils with similar properties. This can be taken as a demonstration of the beneficial effect of organic matter and soil organisms on soil structure.

10 Figure 13 shows soil profiles for a Vetic Nitisol (Hypereutric, Rhodic) in Bolivia (HCC-22), the only Nitisol identified in this study. Cation profiles show that the exchange capacity of this soil is high, with [Ca] and [Mg] accounting for most of it. The vertical distribution of cations shows a gradual decrease with depth, with [Mg] remaining constant throughout the soil profile. At depths above 1.4 m [Mg] becomes the dominant cation in the profile, with other cations appearing just in trace amounts. Clay increases considerably in the subsurface but then experiences a gradual decline with silt contents increasing substantially with depth. Soil carbon is generally high but remarkably so in the soil surface, showing only a small decline with depth. Vertical distribution of carbon, cations and particle size fraction are characteristic of Nitisols, where high cation exchange capacity and high base saturation is often associated with high organic matter content in these soils (Richter and Babbar, 1991). At 170 cm a compact clay layer with scattered rocks having vitric properties constrained sampling to that layer.

3.3.7 Podzols

25 Podzols (Spodosols in US Soil Taxonomy) are soils with whitish grey subsurface horizon, bleached by organic acids, this overlying a dark accumulation horizon with brown or black illuviated humus. Podzols occur in humid areas, in particular in the Boreal and Temperate Zones but locally also in the tropics. In Amazonia they develop over

unconsolidated weathering materials of siliceous rock which are prominent on alluvial, colluvial and aeolian deposits of quartzitic sands. They occur mostly along the Rio Negro and in the northern upper Amazon Basin (Do Nascimento et al., 2004).

During the formation of Podzols, complexes of Al, Fe and organic compounds migrate from the surface soil to the B horizon with percolating rainwater. Podzolization is a combination of processes, including the movement of soluble metal-humus complexes (chelates) out of the surface soil to greater depth (cheluviation), and the subsequent accumulation of Al and Fe chelates in a spodic horizon (Chilluviation; Driessen et al., 2001). There are contrasting views regarding the formation of Podzols in the tropics, most likely with one or another occurring in different environmental conditions. Some authors advocate that Ferralsols and Acrisols (or eroded material from them) can undergo transformations and form Podzols under water saturation, via selective clay removal and lateral movement processes (Lucas et al., 1984; Chauvel et al., 1987; Bravard and Rihgi, 1989; Lucas, 1997; Dubroeuq and Volkoff, 1998; Do Nascimento et al., 2004). Podzols can also evolve locally on vertical pedogenic processes as described by Horbe et al. (2004). Despite their relatively small area (Table 1) Podzols are one of the most studied soil types in Amazonia (Vitousek and Sanford, 1986), with a great variety of studies over its characteristic infertility and tight nutrient cycling (Went and Stark, 1968; Jordan and Herrera, 1981; Jordan, 1989). A comprehensive review of formation and characteristic of Amazonian Podzols is given by Do Nascimento et al. (2004).

Generally these soils have severe acidity, high [Al], low chemical fertility and unfavourable physical properties. The organic matter profile of Podzols usually shows two areas of concentration, one at the surface and one in the spodic horizon, but often erosion of surface horizons can expose the albic horizon (low organic matter, bleached layer) resulting in only one zone of increased organic matter. Usually, high concentrations of Al or Fe occur in conjunction with the spodic horizon, reflecting the concentrations of metal-humus chelates in this zone. The C:N-ratio is typically as high as 50 in the surface horizon, and nutrient levels in Podzols are low as a consequence

BGD

6, 3851–3921, 2009

The soils of RAINFOR Project

C. A. Quesada et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



of a high degree of leaching (Buol et al., 2003). Plant nutrients are concentrated in the surface horizon where impressive root mats often occur (Jordan and Herrera, 1981). Nutrient economy in these soils is highly dependent on the recycling of elements which are released by decomposing organic debris.

5 In hydromorphic Podzols, dissolved organic matter with bound Al, can be transported laterally as shallow groundwater usually restricts vertical transport in the soil and hydro-morphic Podzols in areas with lateral water flow are associated with “black water” rivers and lakes in boreal, temperate and tropical areas (Driessen et al., 2001). The formation of a hardpan by illuviated sesquioxides and organic matter (ortsteinic) is common
10 in podzols where there is periodic water stagnation in the soil, either in the B horizon or below it, and water movement through the soil may be restrictive even in upland areas if the soil has a dense illuviation horizon or an indurate layer (Buol et al., 2003).

In this study, Podzols were found in Brazil, Colombia and Venezuela, usually supporting forests, with a low above ground biomass. Together with the Arenosols (Sect. 3.5.1)
15 they are the most infertile soils in Amazonia and Fig. 14 gives soil profiles for one Ortsteinic Podzol (oxyaquic) in Colombia (ZAR-01). The vegetation over this soil is locally called *Varrillal* which translates to “land of twigs”; it is no more than a stunted forest in which thin and very short trees are abundant. An impressive root mat covers the soil, almost no roots were observed inside the mineral soil itself. The exchangeable bases
20 are very low with most found in the very topsoil. Aluminium constitutes most of the ECEC and an association between base cation concentrations and soil organic matter is obvious; most if not all nutrient exchange must occur in the root mat which keeps the remaining nutrients held within the system. At the start of the ortsteinic layer at approximately 1 m deep, aluminium concentration increased abruptly as did the carbon
25 content. This is taken to reflect the composition of the ortsteinic layer where Al-humus chelates act as cementing substances.

BGD

6, 3851–3921, 2009

The soils of RAINFOR Project

C. A. Quesada et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



3.4 Soils conditioned by topography and drainage

3.4.1 Fluvisols

Fluvisols (Entisols-Fluvents in US Soil Taxonomy) are genetically young soils formed on sediments of alluvial origin (Buol et al., 2003). Their principal morphologic characteristic is the presence of stratification and weak horizon differentiation (Driessen et al., 2001; IUSS Working Group WRB, 2006). They are usually shallow with their fertility strongly dependent on the nature of the material deposited (Irion, 1984; Sanchez, 1976). The only Fluvisol identified in this study (JAS-05) was derived from lateral movements of the Napo River in Ecuador. Fluvisols are a common soil group in Amazonia, especially in its western parts where they occur over large floodplains of recent alluvial origin (Sombroek, 1984; Fig. 4).

Our Fluvisol was identified as a Haplic Fluvisol (Orthodystric), and soil profile data is shown in Fig. 15. Exchangeable bases were relatively high but with low [Al]. Despite such high nutrient concentration, soil was classified as Orthodystric as its base saturation extracted by ammonium acetate pH 7 was only 0.21, a problem discussed further in the methods section. The carbon profile showed a relatively high [C] near the surface, followed by a decline until 0.4 m, rising again at depth, this also being associated with irregular variations with depth for the particle size distributions. These stratification patterns probably reflect the discrete sediment deposition events which are typical for this soil type. The lower portion of the soil profile consisted of rounded rocks similar to that found at the margins of the Napo River itself, suggesting that the area occupied by today's soil was once under or at the river margin. Above that, two different depositional layers were clearly identifiable, with the lower buried soil layer having a relatively higher [C] than the layer immediately above.

BGD

6, 3851–3921, 2009

The soils of RAINFOR Project

C. A. Quesada et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



3.4.2 Gleysols

Gleysols (Entisols-Aquents in US Soil Taxonomy) are soils from wetlands which remain saturated for long enough periods to allow formation of gleyic colour patterns, evidence of reduction processes with or without segregation of iron (Driessen et al., 2001; IUSS Working Group WRB, 2006). They usually occupy lower positions in the terrain and are linked to shallow groundwater. Such soils are formed under excessive wetness at shallow depths in some period of the year or throughout the year. Low redox conditions brought by prolonged soil saturation, in the presence of dissolved organic matter, induce the reduction of ferric iron to mobile ferrous compounds (Osher and Buol, 1998). When iron compounds are mobilized and removed, the soil material shows its own true colours, which normally have a low hue. This is the reason why permanently saturated gleyic subsoil layers have neutral, whitish/greyish or bluish colours (Driessen et al., 2001; Buol et al., 2003). Gleysols in land depressions or at the bottom of slopes are usually comparatively fertile compared to adjacent soils as they tend to have a finer texture, slower organic matter decomposition rates and an alluvial or colluvial influx of nutrients.

Gleysols are common soils in Amazonia (Sombroek, 1966, 1984; Sanchez, 1976; Fig. 4) and in this study Gleysols were found in Peru, Ecuador and Colombia. Two soil profiles are shown here, these representing the two ends of the fertility spectrum. Figure 16a is for Haplic Gleysol (Orthoeutric, Siltic), located in Ecuador (TIP-03). For this soil, exchangeable bases were very high throughout the profile, at least by Amazonian standards, with [Ca] being particularly high, and Al saturation low. Carbon content was, however, only prominent at the very surface soil, which overlaps with their soil layer where some soil structure appears. Below that depth, C contents are low but concentrations are constant throughout the profile. Particle size fractions suggested a silty clay, changing to clay in some soil layers.

The second profile is for a Haplic Gleysol (Alumic, Hyperdystric) in Colombia (ZAR-02, Fig. 16b). Unlike TIP-03, exchangeable bases were low but with the CEC quite high

BGD

6, 3851–3921, 2009

The soils of RAINFOR Project

C. A. Quesada et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



and dominated by [Al]. Despite surface soil C being not as high as in the other Gleysol example, the overall distribution pattern of C is similar in both soils. Nevertheless, in contrast to TIP-03, the clay fraction was very small with silt and sand predominating. Soil particle size was constant throughout the profile, having a sandy loam texture.

From the above comparison it is evident that, as for Cambisols (Sect. 3.1.2), Gleysols can encompass soils of a wide range of fertilities and textures and with incipient weathering due to perching water often resulting in little differentiation throughout the profile. For most gleysols physical properties are, however, restrictive; both by water saturation and incipient development of subsurface horizons. Although such soils are usually deep, effective rooting depths are often limited, this being due to constraints imposed by a high bulk density, limited oxygen supplies, soil compactness and water saturation.

3.4.3 Umbrisols

Umbrisols (Umbric Great Groups in US Soil Taxonomy) are a reference group of young soils thought to be restricted to high altitudes, and according to that are not even mapped in the SOTERLAC Database as occurring in Amazonia. The main characteristic of these soils is the development of an umbric surface horizon, without any other mature diagnostic subsurface horizon. Organic matter is thought to accumulate in such soils as a result of low temperatures. They may share some characteristics with Cambisols but a higher position in the classification key gives them prevalence. An umbric horizon is a thick, dark coloured surface horizon with low base saturation and rich in organic matter. No other diagnostic horizon may be present apart of an anthropogenic, an albic or a cambic horizon (Driessen et al., 2001).

Although at odds with the idea of having an umbric layer arising only as a result of lower temperatures in mountainous regions (IUSS Working Group WRB, 2006), two adjacent profiles in the lowland forests of Bolivia were classified in this work as Umbrisols and Fig. 17 shows profiles for LSL-01, an Endogleyic Umbrisol (Alumic, Hyperdystric). Following Umbrisol classification requirements, dark organic matter dominates the surface soil. Exchangeable bases are low, with the CEC dominated by Al with the particle

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



size profile showing a dominance of clay loam. Both clay and sand showed some increment starting at 0.5 m but it is impossible to tell where they extended as our sampling stops at 0.7 m due to groundwater being reached.

Perhaps a mistake could have been made during the classification of these soils as our sampling profile was limited in depth by groundwater but the WRB soil classification system led unequivocally to us keying these soils out as such. If not Umbrisols, these soils in Bolivia would probably be classified as Cambisols or perhaps Gleysols. A similar situation is reported by Schad et al. (2001), who found several Phaeozems in lowland Bolivia. Phaeozems are fertile soils with mollic or umbric surface horizons, which had been thought to be exclusively associated to the steppes of temperate regions. As a new RSG in the WRB system, it seems likely that some Umbrisols apparently outside the central concept and characteristics will appear. It is possible that some additional characteristics will be required to fully separate these soils into meaningful sub-categories.

3.5 Soils conditioned by parent material

3.5.1 Arenosols

Arenosols (Entisols-Psamments in US Soil Taxonomy) are poorly studied soils, most likely a consequence of their limited agricultural importance. This is despite their considerable worldwide extent, covering 900 million ha globally compared with 700 million ha of Ferralsols (Hartermink and Huting, 2008). In Amazonia, their coverage area is much lower (0.027 of the area, approximately 20 million ha, Table 1). Arenosols are characterized by coarse textures which must be derived from sand rich parent materials transported by wind, water or in some cases, locally weathered and deposited in colluvial zones through selective erosion (Driessen et al., 2001; Buol et al., 2003; IUSS Working Group WRB, 2006). Arenosols are generally weakly developed, with little horizon differentiation. Characteristic properties of such soils are high water permeability, low water holding capacity, low specific heat, and often minimum nutrient

BGD

6, 3851–3921, 2009

The soils of RAINFOR Project

C. A. Quesada et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



5 contents (van Wambeke, 1992). The limited potential of these soils to supply nutrients must come almost exclusively from mineralization of organic matter. In a recent study, Hartermink and Huting (2008) showed that cation exchange capacity in 150 Arenosols of Southern Africa varied markedly with small increments in clay content, CEC ranged
10 from about 10.0 to 90.0 mmol_c kg⁻¹, varying linearly along a change in clay content of only 0.12. A similar relationship was also found in soil carbon content which varied from about 0.5 to 12 g kg⁻¹ for a similar change in clay. Carbon concentrations and CEC were also linearly related suggesting that organic matter is the major source of
15 nutrients. However, the African Arenosols studied seem to be much more fertile than the Amazonian one. For example, the CECs for both Arenosols found in this study were less than 4.0 mmol_c kg⁻¹. Although these soils often support savannas or grasslands in the tropics, they are also found under short forests and even under lowland tropical forests in Amazonia (Sanchez, 1976; Sombroek, 1966, 2000). In places where evaporative demand exceeds water supply, water deficit is considered a major problem
20 for vegetation (Sanchez, 1976), although roots are often found in this soils extending to considerable depths.

Figure 18 show soil profiles for a Haplic Arenosol (Hyperdystric) in northern Peru. Exchangeable bases and aluminium are extremely low with most of the cations pool present at the very top soil, most likely reflecting nutrients held on soil organic matter.
25 Fertility of such soils is extremely dependant on biological cycles which maintain nutrients held in the biomass (Sombroek, 1966) with soil carbon concentration also very low and declining dramatically with depth. The low carbon and cations concentrations both reflect the characteristic coarse soil texture of Arenosols.

3.5.2 Andosols

25 Andosols (Andisols in US Soil Taxonomy) are dark soils developed on volcanic materials. They mostly occur in undulating to mountainous zones in, humid, arctic to tropical regions and under a wide range of vegetation types. They are formed through rapid weathering of porous volcanic material which results in accumulation of stable organo-

BGD

6, 3851–3921, 2009

The soils of RAINFOR Project

C. A. Quesada et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



mineral complexes and short range order minerals such as allophane, imogolite and ferrihydrite (Richter and Babbar, 1991; Shoji et al., 1993; Driessen et al., 2001). Their coverage in Amazonia is small and mostly restricted to mountain regions in the Andes, usually occurring under cloud forests. Therefore, Andosols should not be thought of as common soils under lowland tropical vegetation.

Following the description in Driessen et al. (2001), these soils are characterised by the presence of either an andic horizon or a vitric horizon. An andic horizon is rich in allophanes and similar minerals, or aluminium humus complexes whereas a vitric horizon contains volcanic glass. Andosol formation depends essentially on rapid chemical weathering of porous, permeable, fine-grained mineral material in the presence of organic matter. The high [Al] protects the organic component of the Al humus complex against biological decay. The mobility of these complexes is limited because rapid weathering yields sufficient Al and Fe to produce complexes with a high metal/organic ratio which have moderate solubility. Together, the low mobility and high resistance to biological degradation promotes an accumulation of organic matter in the topsoil which culminates in the formation of a melanic surface horizon with high organic matter content. The average organic matter content of the surface horizon is about 80 mg g^{-1} but the darkest profiles may contain as much as 300 mg g^{-1} organic matter. Soil bulk density is usually low in such soil, a consequence of increments in the pore fraction as weathering advances. The dominant type of clay changes over time, particularly in the subsoil, as allophane and imogolite are transformed to other clay minerals such as halloysite, kaolinite or gibbsite. Aluminium from the Al humus complexes gradually becomes available, with ferrihydrite eventually turning into goethite. Eventually, Andosols may evolve into a more mature soil, as a podzol, or a soil with ferric properties or clay illuviation.

Only one Andosol was identified in this study, a Silandic Andosol (Hyperdystric, Siltic), under a sub-montane forest near the Sumaco volcano, Ecuador (SUM-06). For this soil, exchangeable cations were relatively high at the surface (Fig. 19), but declining dramatically with depth. Soil carbon reached nearly 200 mg g^{-1} at the very topsoil

**The soils of
RAINFOR Project**C. A. Quesada et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

in association with exchangeable Al, possibly indicating dominance of Al humus complexes at that depth. Nevertheless, the organic matter concentration was reasonably high throughout the profile. The finer fractions of the soil decreased almost steadily with depth, most likely reflecting the influence of low weathering levels and with the subsurface horizons still lacking development.

3.6 Other soils

A few soil groups known to occur in the humid tropics were not represented in this study, and because of their limited area coverage and are not extensively discussed here. These include the Solonchaks, Solonetz, Phaeozems, Regosols, Histosols and Luvisols. The first two soil groups are unlikely to be found under forest vegetation in Amazonia as Solonchaks are imperfectly drained, salt rich soils typical of coastal regions with the Solonetz being another Na-rich soil group. Phaeozems are fertile, wet soils with characterised by an extensive accumulation of organic matter and again with only a very limited cover in Amazonia.

On the other hand, Regosols, Histosols and Luvisols probably have a wider distribution beneath Amazonian vegetation. Regosols are classified as suborders Orthents and Psammets in the Soil Taxonomy and are thin soils derived from unconsolidated material and lacking diagnostic horizons. They are thus soils with incipient development. Histosols are soils with >0.30 organic matter at the surface, usually occurring in Amazonia only in landscape depressions and wetlands, mostly appearing in small patches associated with other soils. Luvisols are similar to Alfisols in the Soil Taxonomy system; their principal characteristics are clay illuviation and both a high ECEC and a high base saturation. Despite their limited range in the moist tropics of South America his makes them very valuable for agriculture and also for ecological studies (Richter and Babbar, 1991; Sanchez and Buol, 1975).

BGD

6, 3851–3921, 2009

The soils of RAINFOR Project

C. A. Quesada et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



3.7 Linking WRB reference soils groups to a general scheme of soil genesis

From the above analysis, it is clear that the soils of Amazonia encompass a considerable diversity with observed variations in physical and chemical properties strongly associated with state of pedogenic development (Quesada et al., 2009a). To allow such an analysis and to contextualize this diversity in a soil evolutionary frame, a scheme of pedogenic development is thus proposed (Fig. 20). The ordination of the soils was made on the basis of their genetic, chemical and morphological characteristics, typical mineralogy and interpretation of the effects of local soil forming factors.

In the very early stages of soil formation, different parent materials give rise to what should be the first source of variability in soils. The first soils to evolve from rocks are thus considered to be the Leptosols which are very shallow soils, with incipient weathering of parent material. If the weathering of the subsurface soil occurs at higher rates than surface erosion such soils will most certainly reach a Cambisol stage (Buol et al., 2003). Nevertheless, many soils in Amazonia develop over deposited sediments and if drainage conditions are good, such sediments would most likely evolve to a Regosol stage, equivalent to Leptosols but of a sedimentary origin. After that, different paths of soil formation may occur depending on drainage extent. If sediments are water saturated for a long time Gleysols may be formed. These can thus be considered to be genetically young soils, with very little profile development and with this condition being maintained by continuous or periodic water saturation. But if sediments have been deposited in different recent events, a stratified profile may be formed giving rise to the formation of Fluvisols. Although Fluvisol drainage conditions are usually better than Gleysols, seasonal saturation of the subsoil should still maintain such soil with at a low level of pedogenic development.

Moisture regime and landscape position are possibly the most important factors determining soil formation at these early stages, and development towards other soil types may demand some drastic changes in the landscape and water regime (Fritsch et al., 2006). Nevertheless, provided that sufficient changes in drainage occur, Gleysols

BGD

6, 3851–3921, 2009

The soils of RAINFOR Project

C. A. Quesada et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**The soils of
RAINFOR Project**C. A. Quesada et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

probably should evolve into more mature soils, most likely involving a Cambisol stage, followed by the development of argic or plinthic horizons. Fluvisols may also develop to Cambisols once they are now longer exposed to new depositional events. However, changes in drainage may also occur increasing water saturation in the profile and this which could result in transformation of iron to ferrous compounds and formation of Gleysols. Also, some types of parent material can lead to a special variation in soil type, for instance volcanic material would most invariably lead to the formation of Andosols. The unique Andosol found in this study had the characteristics of a poorly developed soil, thus it was assumed to have a transient condition equivalent to an intermediary position close to Cambisols.

Cambisols are soils showing early signs of horizon differentiation usually occurring associated with steep topography in Amazonia, but unless erosion keeps pace with subsoil weathering, they will evolve and give rise to more mature soil groups (Buol et al., 2003). The most important factors influencing Cambisol transformations towards other soil groups are topography position and parent material; leading to a large variations in the magnitude of the numerous processes and mineralogical reactions giving rise to distinct routes of soil formation. Cambisols can thus be considered soils in a transitional state, prior to the development of spodic, ferralitic and different types of soils with argic horizon (Buol et al., 2003).

Umbrisols are typical of cool mountain landscapes where temperature controls over decomposition allow the formation of thick humus layer on the topsoil (umbric horizon). Usually there is no other diagnostic horizon present but cambic horizons may be present (Driessen et al., 2001). In this study, some lowland soils in Amazonia did key out as Umbrisols, as this group has priority over Cambisols which would probably be their classification if they did not key out beforehand. Here, Umbrisols were tentatively placed after Cambisols compromising their incipient subsurface development and the development of umbric horizon.

The intermediate-mature phase of soil development includes some soils with much more similar weathering levels which makes separation more difficult. Some of these

**The soils of
RAINFOR Project**C. A. Quesada et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I◀](#)[▶I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

soils share great morphological similarities and thus differentiation among them has been done considering mineralogy and clay activity, cation exchange capacity and characteristics of nutrient release in vertical soil profiles along with soil morphology. Alisols are high CEC soils in which high activity clays accumulate in a subsurface horizon. Their mineralogy is dominated by Al bearing secondary clay minerals such as smectite and vermiculite. Such minerals are formed from the alteration of micas, most commonly found in Cambisols, suggesting Alisols have some developmental proximity to this soil type. Also active weathering of 2:1 high activity clay minerals still seems to release aluminium and some base cations to the soil solution with this varying with depth, suggesting different levels of weathering occurring between surface and subsurface horizons. The presence of clay illuviation places Alisols in a higher evolutionary stage than the previously discussed soils, but its higher CEC, its high activity clay mineralogy and vertical pattern of weathering/nutrient release suggests that Alisols have a lower level of pedogenic development than the remaining soil groups.

Plinthosols follow a somewhat different route of formation, being strongly influenced by fluctuation of groundwater, most likely evolving from Gleysols, Fluvisols and some Cambisols with aquic properties. They are placed after Alisols due to their lower CEC but still have similar chemical characteristics and also due to their mineralogy which is in the course of alteration towards the formation of kaolinite and sesquioxides. Plinthosols are tentatively separated here from Nitisols, Lixisols and Acrisols, by the ongoing removal of silica and bases and subsequent segregation of iron.

Nitisols can be placed between Plinthosols and the remaining soils with argic horizon due to their mineralogy and intermediate age morphologic characteristics and with Lixisol and Acrisol differentiation made on the basis of weathering of parent material which still supplies adequate amounts of exchangeable bases for Lixisols, while Acrisols do not show any sign of active mineral weathering in their subsoil.

Acrisols are easily separated from Ferralsols on the basis of their contrasting morphologies, mineralogy and chemistry. For example, unlike Acrisols, Ferralsols do not have significant signs of clay illuviation, and have reached complete desilication and

**The soils of
RAINFOR Project**C. A. Quesada et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

transformation of clay minerals toward kaolinite and Fe and Al oxides. Ferralsols might be the final stage of weathering in many conditions but further transformation to Podzols via selective clay removal under water saturation and lateral movement processes has been suggested (Dubroeuq and Volkoff, 1998; Lucas, 1997; Bravard and Rihgi, 1989; Chauvel et al., 1987; Lucas et al., 1984). Usually, Ferralsols show no tendency to develop an elluvial horizon but they may transform to Podzols if iron compounds are removed, and the clay is decomposed by ferrololysis under conditions of periodic water stagnation. This might occur on colluvial deposits transported from Ferralsols down slope. Nevertheless, Podzols can also develop as a consequence of vertical pedogenic processes, following the formation of white sands (Horbe et al., 2004).

Arenosols usually have depositional origin but can also be formed under weathering of quartz rich rocks. As conditioned by their parent material, they show very little horizon differentiation and for that reason are often considered young soils (IUSS Working Group WRB, 2006). Nevertheless, many Arenosols in the Amazon Basin seem to derive from old reworked sediments originated from the Guyana shield (Fittkau et al., 1975). Their soil chemistry is also characteristic of the “terminal stages” of pedogenesis (Quesada et al., 2009a) and for those reasons are assumed to belong to older development surfaces.

Figure 21 shows the relationship between the suggested axis of pedogenic development and a chemically based weathering index (Total Reserve Bases, Σ_{RB}), which is taken to represent an estimation of weatherable minerals (Delvaux et al., 1989). To account for variations within the soil groups, each Reference Soil Group was further divided into subgroup types representing the principal distinctions in the lower taxonomic levels (the table with Fig. 21 gives taxonomic details for RSG lower classification levels). This chemical weathering index showed good agreement with the proposed nature of the soil age gradient. Soils with lower pedogenic development all had high levels of Σ_{RB} , with the higher values occurring in Cambisols, Fluvisols and Gleysols, after which Σ_{RB} then declines gradually as pedogenic development increases, reaching its lowest values in the Podzols. Such changes along the pedogenic gradient are likely to

be associated with relative concentration of weatherable minerals, changes in mineral assemblage through processes such as desilication, neoformation and kaolinization and changes in surface area and charge characteristics associated with changes in the mineral matrix (Uehara and Gilman, 1981). Variations within soil lower levels were also found, and in general, nomenclature for lower taxonomic levels was successful in grouping similar soils. Within each soil group, the prefixes for the lower levels characterize individual morphological features but on some occasions also helped to differentiate soils in terms of fertility and weathering level. For instance, Ferralsols named with suffix “Geric Acric” had higher Σ_{RB} than the “Geric” ones, as did “Endostagnic” Plinthosols in relation to “Haplic Plinthosols”, independently of sharing the same fertility suffixes. This may indicate that the chemical and morphological characteristics described by the Σ_{RB} suffixes and prefixes reflect intergrades of weathering and possibly differences in parent material. However, other subgroups in Alisols and Acrisols appeared to be less divergent in relation to weathering with no clear differentiation in Σ_{RB} .

In the World Reference Base a more precise level of fertility is usually described by qualifier suffixes which, in the case of this study, had “Orthoeutric”, “Hyperdystric” and “Alumic Hyperdystric”. This was particularly informative for Cambisol group, where a distinct gradient was observed among the three lower level soils. Levels of fertility and weathering in these soils were clearly separated by the different suffixes, irrespective of the prefix variations associated with morphological characteristics.

Finally, during the process of soil classification, it was observed that soils with relatively high levels of fertility were often classified as Hyperdystric with the actual differentiation for the exceptionally infertile soils only made by the suffix Alumic Hyperdystric, which represents the clear dominance of aluminium over exchangeable bases. Therefore, soils with the qualifier suffix Hyperdystric (when not associated with suffix Alumic) should be taken as comparatively fertile soils in Amazonia (Quesada et al., 2009a).

The diagram in Fig. 20 shows a simplified route for soil pedogenic development. But actual soil formation and evolution is, of course, far more complex. Short cuts in the soil formation process are known to occur. Moreover, rejuvenating processes might

**The soils of
RAINFOR Project**C. A. Quesada et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I◀](#)[▶I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

**The soils of
RAINFOR Project**C. A. Quesada et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I◀](#)[▶I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

change the direction of soil development. On other occasions, the saprolite from which soils evolve might already have been well weathered during ancient times, thus leading to the direct formation of highly weathered soils like Ferralsols (Buol et al., 2003). Soils can also become the parent material for other soils if dramatic changes in weather or topography have occurred, as well as can be buried, transported and re-deposited, and even disappear if totally eroded. Nevertheless, irrespective of development pathway, soils tend to change their characteristics through time, and so will ultimately develop to genetically mature forms. Clear changes in morphology, chemistry and mineralogy will occur during this process and such variation ultimately has a profound effect over the vegetation structure, dynamics and composition (Quesada et al., 2009b).

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RAINFOR Project**C. A. Quesada et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I◀](#)[▶I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

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BGD

6, 3851–3921, 2009

**The soils of
RAINFOR Project**

C. A. Quesada et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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BGD

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**The soils of
RAINFOR Project**

C. A. Quesada et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**The soils of
RAINFOR Project**C. A. Quesada et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I◀](#)[▶I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

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C. A. Quesada et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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BGD

6, 3851–3921, 2009

**The soils of
RAINFOR Project**

C. A. Quesada et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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BGD

6, 3851–3921, 2009

**The soils of
RAINFOR Project**

C. A. Quesada et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**The soils of
RAINFOR Project**

C. A. Quesada et al.

Table 1. Soil area beneath forest vegetation in Amazonia.

Reference Soil Group	Area (1×10^6 km ²)	Cover fraction
Ferralsols	2.350	0.316
Acrisols	2.154	0.289
Plinthosols	0.648	0.087
Gleysols	0.615	0.083
Cambisols	0.418	0.056
Leptosols	0.405	0.054
Arenosols	0.200	0.027
Fluvisols	0.187	0.025
Regosols	0.144	0.019
Lixisols	0.142	0.019
Podzols	0.141	0.019
Alisols	0.020	0.003
Histosols	0.016	0.002
Nitisols	0.002	<0.001
Total	7.444	1

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Table 2. Glossary of WRB qualifiers used through the text. For complete description of soil classification terms see IUSS working group WRB (2006), report 103.

Qualifier	Description
Acric	Soils having argic horizon, low activity clay and low base saturation. Occur as prefix qualifier in soils where other diagnostic properties have prevalence (i.e. Acric Ferralsol)
Cutanic	Having clay coatings in some part of an argic horizon
Endogleyic	Having reducing conditions between 0.5 and 1 m from surface AND gley colour patterns in 0.25 or more of the soil volume
Endostagnic	Having stagnic colour patterns and reducing conditions
Geric	Soils with very low ECEC
Gibbsic	Having 0.25 or more gibbsite in the fine earth fraction
Haplic	Indicates soils not associated to any specific or intergrade qualifier. Used only when no other prefix apply
Hyperalic	In Alisols only: soils having silt/clay ratio <0.06 and Al saturation ≥ 0.5
Hyperskeletic	Having less than 0.2 fine earth fraction by volume
Ortsteinc	Having a cemented spodic horizon
Silandic	In Andosols only: having one or more layer with andic properties AND $Si_{ox} \geq 0.06$ OR an Alpy to Al_{ox} ratio of less than 0.5
Vetic	Having ECEC of less than $60 \text{ mmol}_c \text{ kg}^{-1}$ clay in some layer within 1 m from surface
Alumic	Having Al saturation ≥ 0.5 in some layer between 0.5–1 m from surface
Ferric	Having an horizon with segregation of Fe or Fe and Mn
Oxyaquic	Saturated with O_2 rich water for more than 20 days AND no gleyic or stagnic colour pattern
Orthodystric	Base saturation ≤ 0.5 throughout between 0.2 and 1 m from surface
Hyperdystric	Base saturation ≤ 0.5 throughout between 0.2 and 1 m from surface AND <0.2 base saturation in some layer within 1 m from surface
Orthoeutric	Base saturation ≥ 0.5 throughout between 0.2 and 1 m from surface
Hypereutric	Base saturation ≥ 0.5 throughout between 0.2 and 1 m from surface AND ≥ 0.8 base saturation in some layer within 1 m from surface
Siltic	Having texture of silt, silt loam, silt clay loam or silt clay in a layer ≥ 0.3 m within 0.5 and 1 m from surface
Clayic	Having a texture of clay in a layer ≥ 0.3 m within 1 m from surface
Arenic	Having a texture of loamy fine sand or coarser in a layer ≥ 0.3 m within 1 m from surface
Xanthic	Very yellow soils
Rhodic	Very red soils

**The soils of
RAINFOR Project**

C. A. Quesada et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The soils of
RAINFOR Project

C. A. Quesada et al.

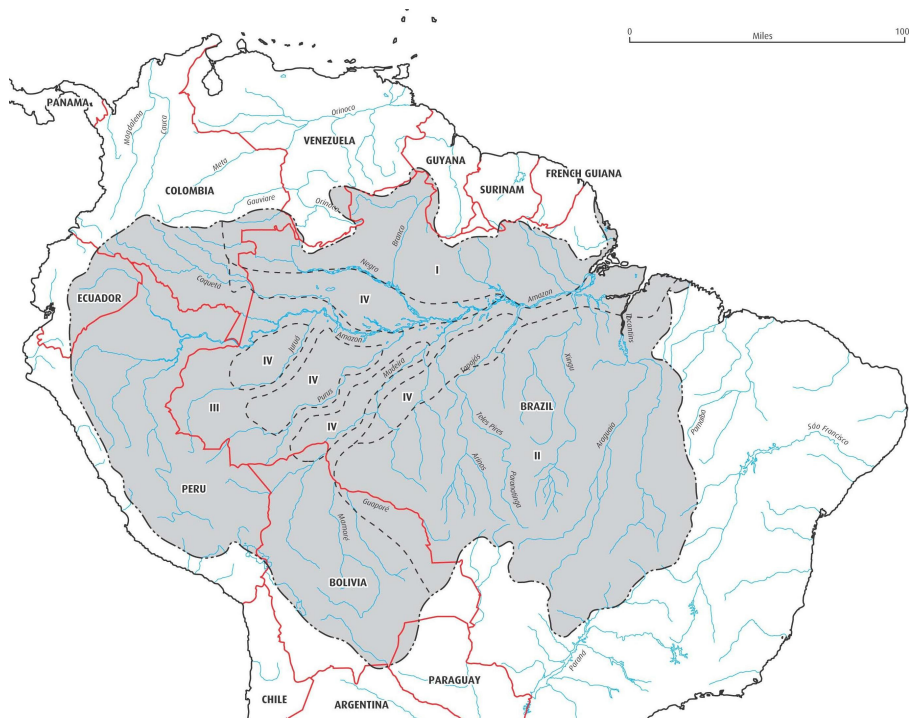


Fig. 1. Division of the Amazon Basin fertility regions according to Fittkau (1971). I) Guyana shield; II) Brazilian shield; III) Western peripheral area and IV) Central Amazonia.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



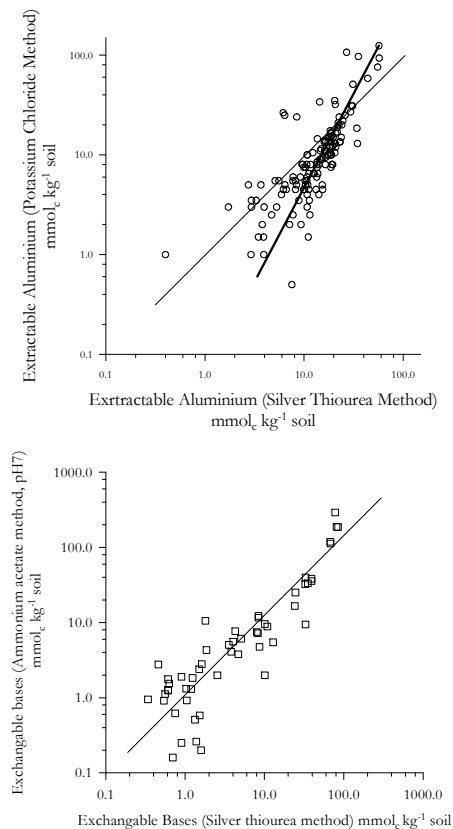


Fig. 2. Cation extraction methods compared: **(a)** relationship between KCl versus AgTU extractable aluminium. **(b)** Exchangeable bases extracted by NH₄Ac at pH 7 as a function of AgTU exchangeable bases.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I◀](#)[▶I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

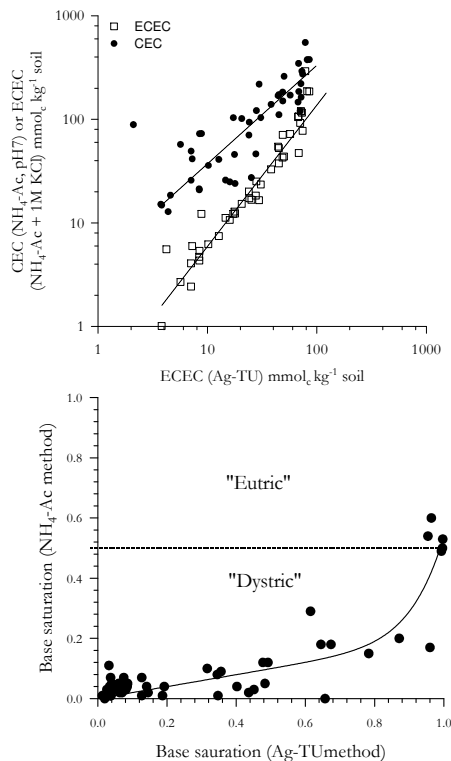


Fig. 3. Cation extraction methods compared. **(a)** Cation exchange capacity (CEC) as determined by NH₄Ac (pH 7) and effective CEC (ECEC) as estimated by summing extractable bases (NH₄Ac) and extractable aluminium (KCl) together, both plotted as a function AgTU extracted ECEC (sum of bases plus aluminium) **(b)** Base saturation calculated using NH₄Ac (pH 7) as a function of base saturation estimated with AgTU.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**The soils of
RAINFOR Project**

C. A. Quesada et al.

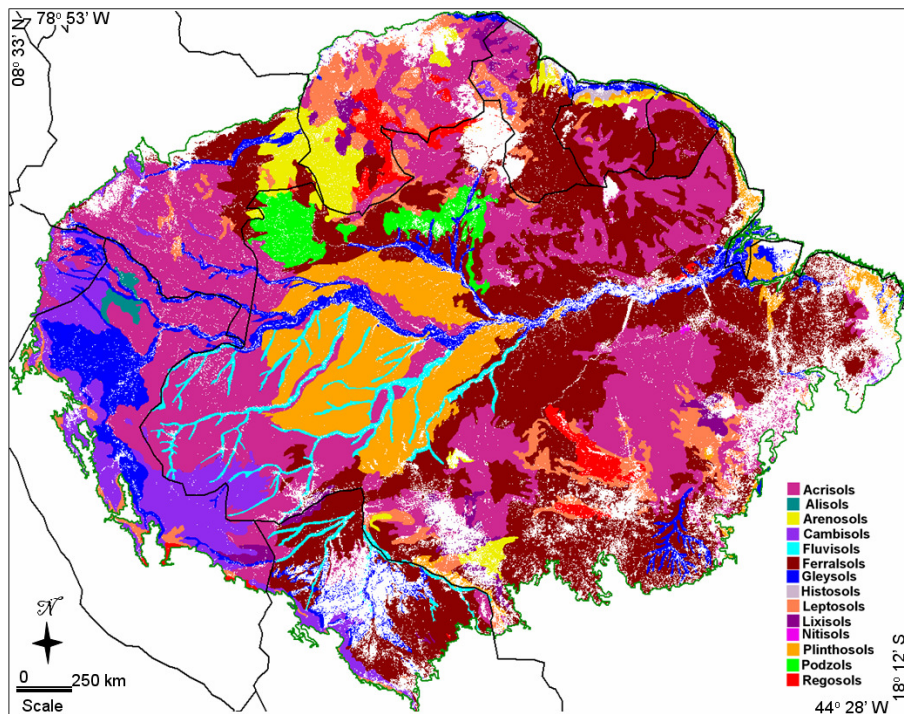


Fig. 4. Basin wide distributions of soils under forest vegetation. Map based on the SOTERLAC-ISRIC soil database (version 2.0, 1.5 million scale) and the vegetation database of Saatchi et al. (2009) for South America.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





Fig. 5. Forest vegetation above a Leptosol in Venezuela (ELD-34).

BGD

6, 3851–3921, 2009

**The soils of
RAINFOR Project**

C. A. Quesada et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The soils of
RAINFOR Project

C. A. Quesada et al.

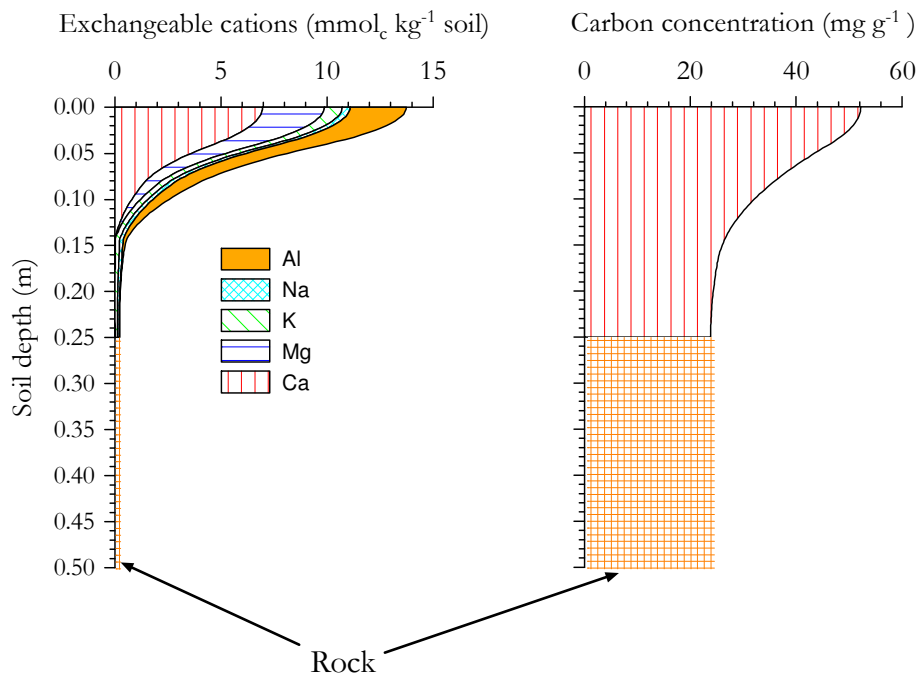


Fig. 6. Profiles of exchangeable cations and soil carbon for a Hyperskeletal Leptosol (Orthodystric) in Venezuela (ELD-34).

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



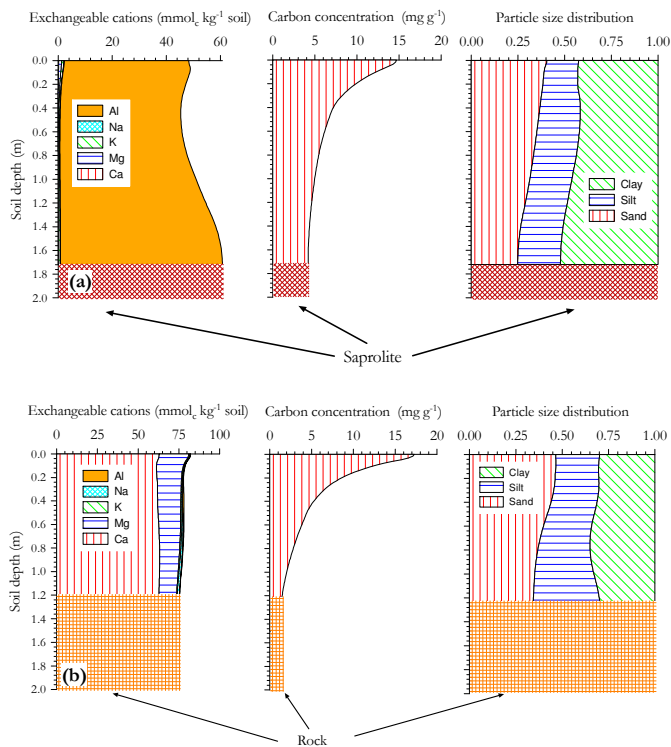


Fig. 7. Profiles of exchangeable cations, soil carbon and texture for **(a)** a Haplic Cambisol (Alumic, hyperdystric, Clayic) in South Peru (TAM-05) and **(b)** a Haplic Cambisol (Orthoetric) in Ecuador (BOG-02).

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



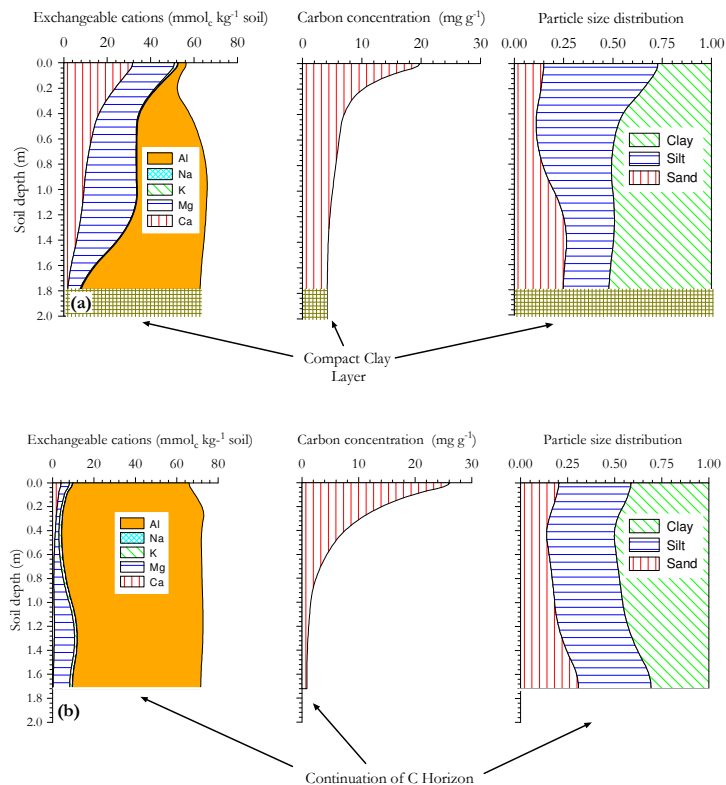


Fig. 8. Profiles of exchangeable cations, soil carbon and texture: **(a)** for a Haplic Plinthosol (Alu-Orthodystric, Siltic), at Acre state, Brazil (DOI-02) and **(b)** for an Endostagnic Plinthosol (Alu-Hyperdystric) in Colombia (AGP-02).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



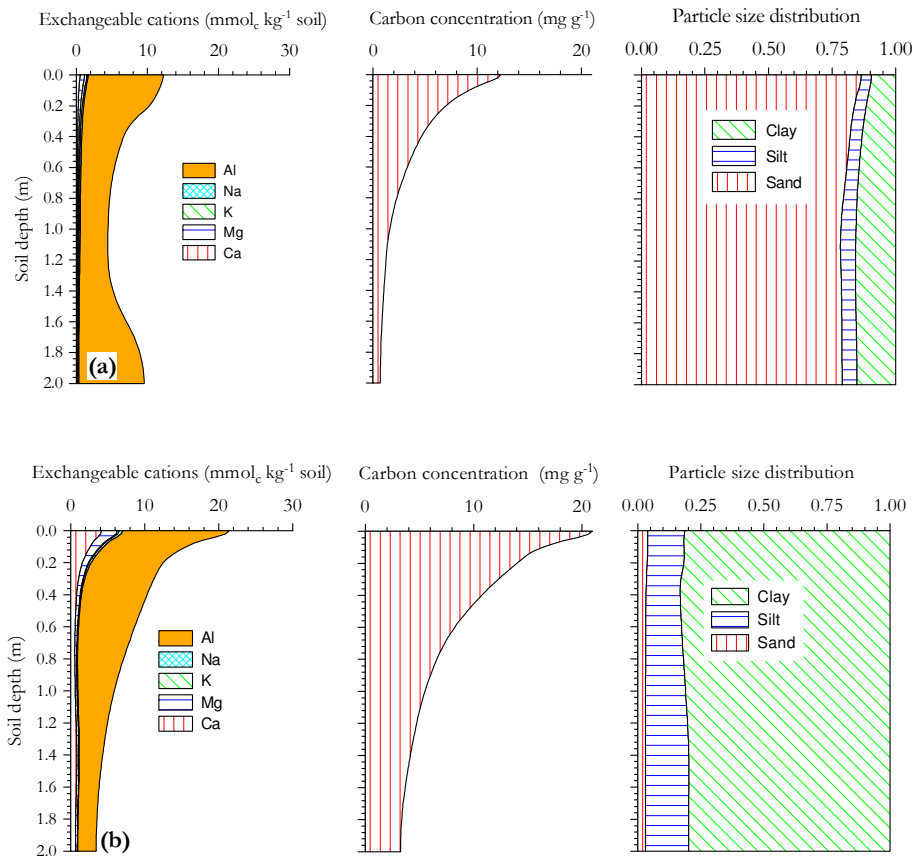


Fig. 9. Profiles of exchangeable cations, soil carbon and texture: **(a)** for a Geric Acric Ferralsol (Alumic, Hyperdistric, Arenic) at Mato Grosso state, Brazil (SIN-01) and **(b)** for a Gibbsic Geric Ferralsol (Alumic, Hyperdistric, Clayic, Xanthic) at Amapá state, Brazil (JRI-01).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



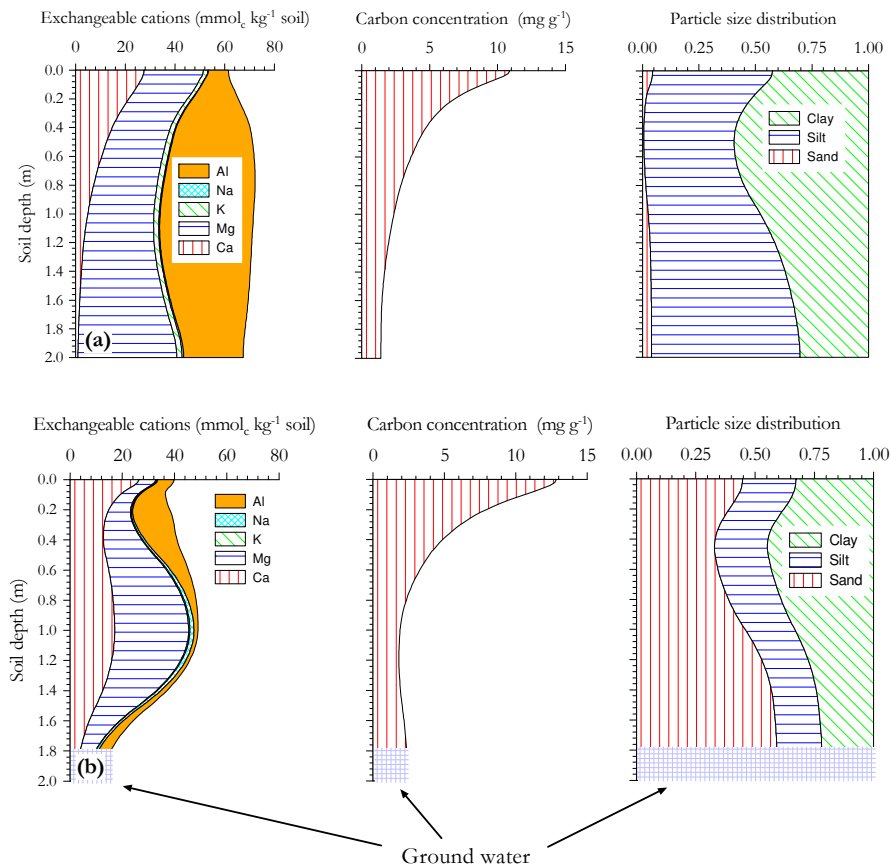


Fig. 10. Profiles of exchangeable cations, soil carbon and texture: **(a)** for a Haplic Alisol (Hyperdystric, Siltic) in South Peru (TAM -06) and **(b)** for a Hyperalic Alisol (Hyperdystric, Clayic) in Ecuador (TIP-05).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The soils of
RAINFOR Project

C. A. Quesada et al.

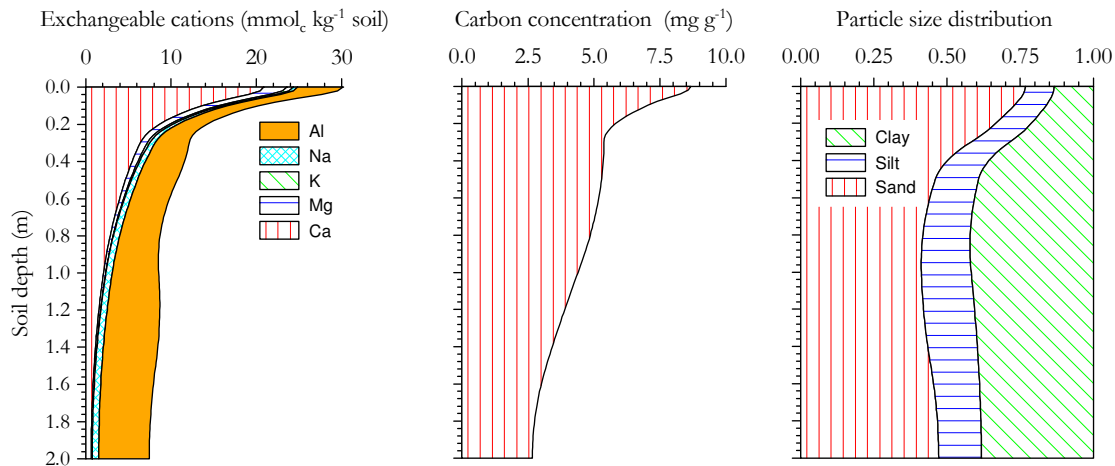


Fig. 11. Profiles of exchangeable cations, soil carbon and texture for a Vetic Acrisol (Hyperdystric) at Mato Grosso state, Brazil (ALF-01).

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The soils of RAINFOR Project

C. A. Quesada et al.

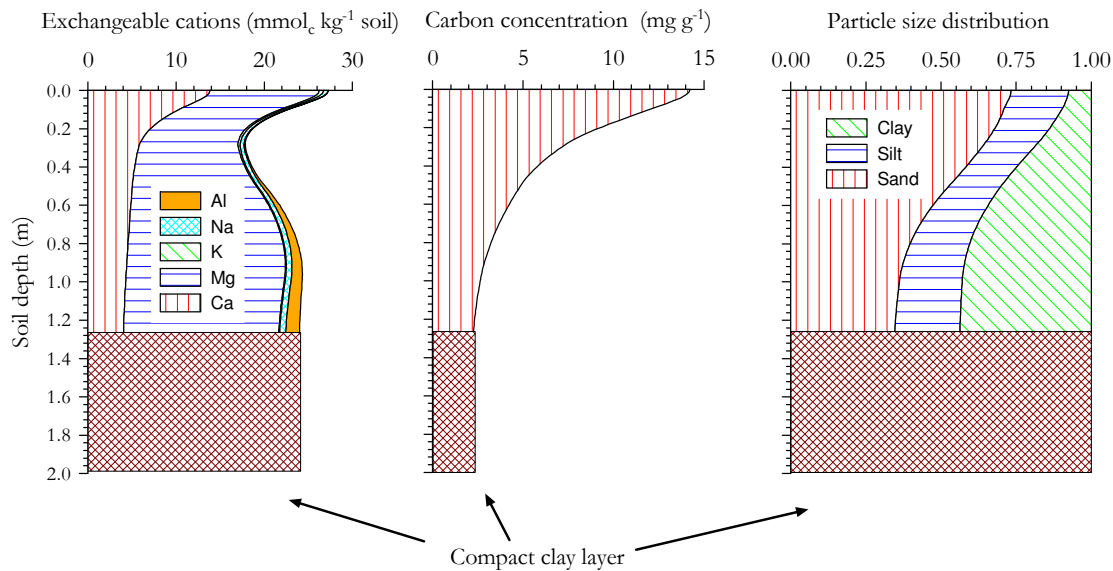


Fig. 12. Profiles of exchangeable cations, soil carbon and texture for a Cutanic Lixisol (Ferric, Hypereutric) in Venezuela (RIO-12).

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The soils of
RAINFOR Project

C. A. Quesada et al.

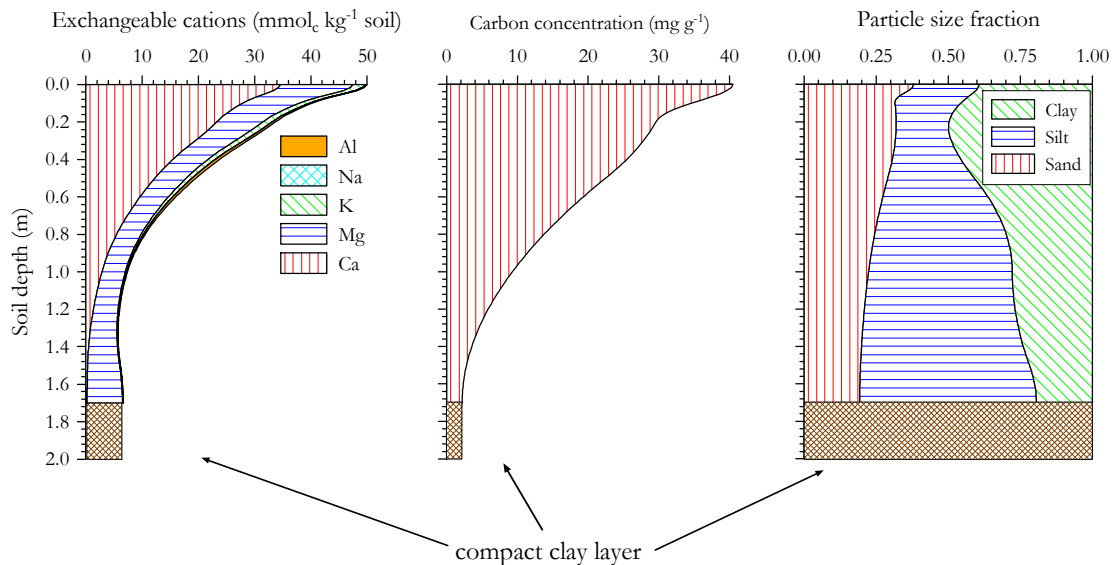


Fig. 13. Profiles of exchangeable cations, soil carbon and texture for a Vetic Nitisol (Hypereutric, Rhodic) in Bolivia (HCC-22).

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The soils of
RAINFOR Project

C. A. Quesada et al.

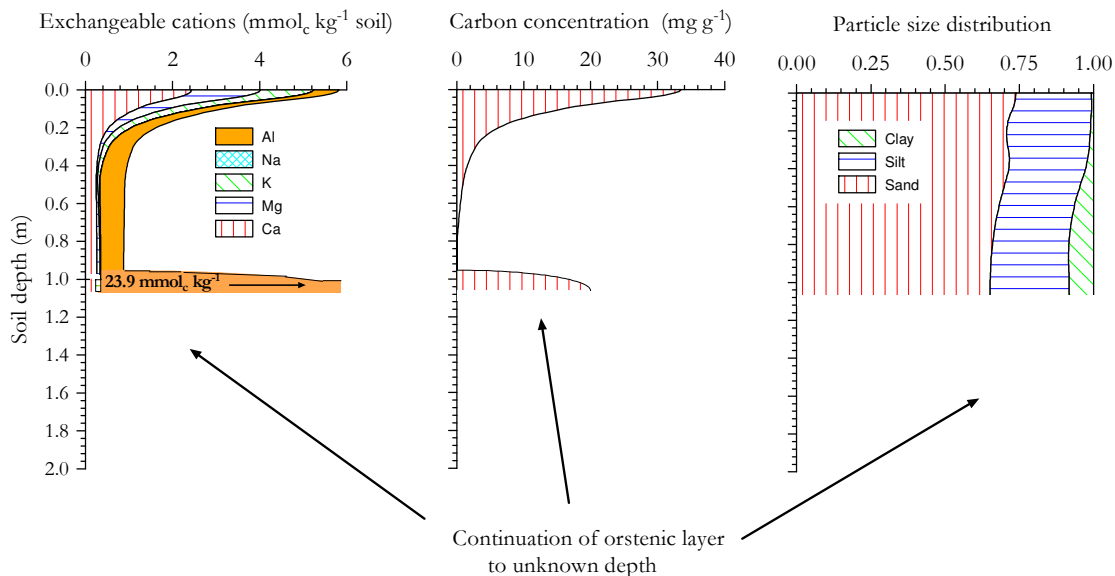


Fig. 14. Profiles of exchangeable cations, soil carbon and texture for a Ortsteinc Podzol (oxyaquic) in Colombia (ZAR-01).

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The soils of
RAINFOR Project

C. A. Quesada et al.

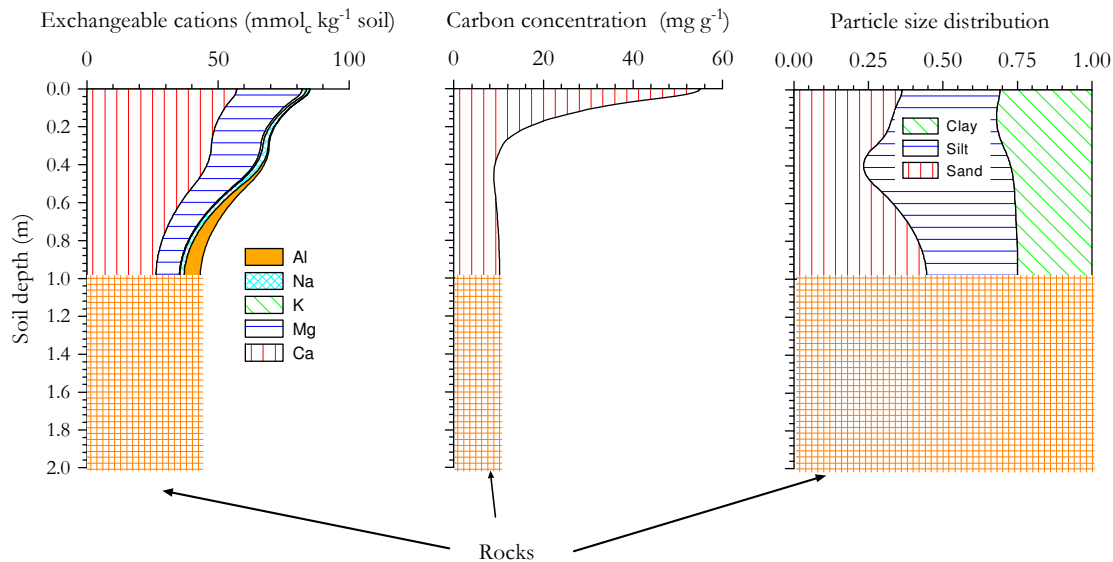


Fig. 15. Profiles of exchangeable cations, soil carbon and texture for a Haplic Fluvisol (Orthoystic) in Ecuador (JAS-05).

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The soils of RAINFOR Project

C. A. Quesada et al.

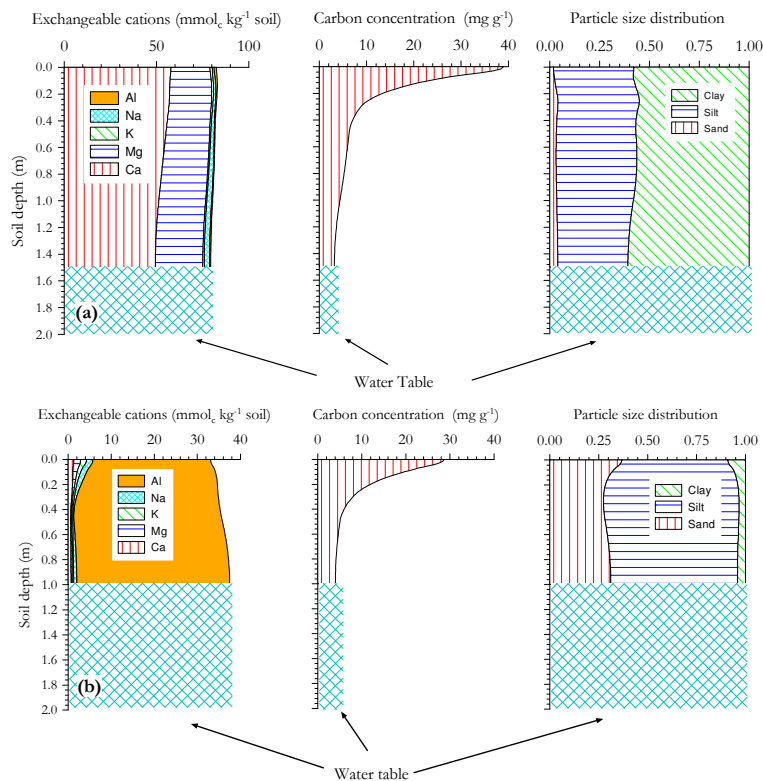


Fig. 16. Profiles of exchangeable cations, soil carbon and texture for **(a)** a Haplic Gleysol (Orthoeutric, Siltic) in Ecuador (TIP-03) and **(b)** for a Haplic Gleysol (Alumic, Hyperdystric) in Colombia (ZAR-02).

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The soils of
RAINFOR Project

C. A. Quesada et al.

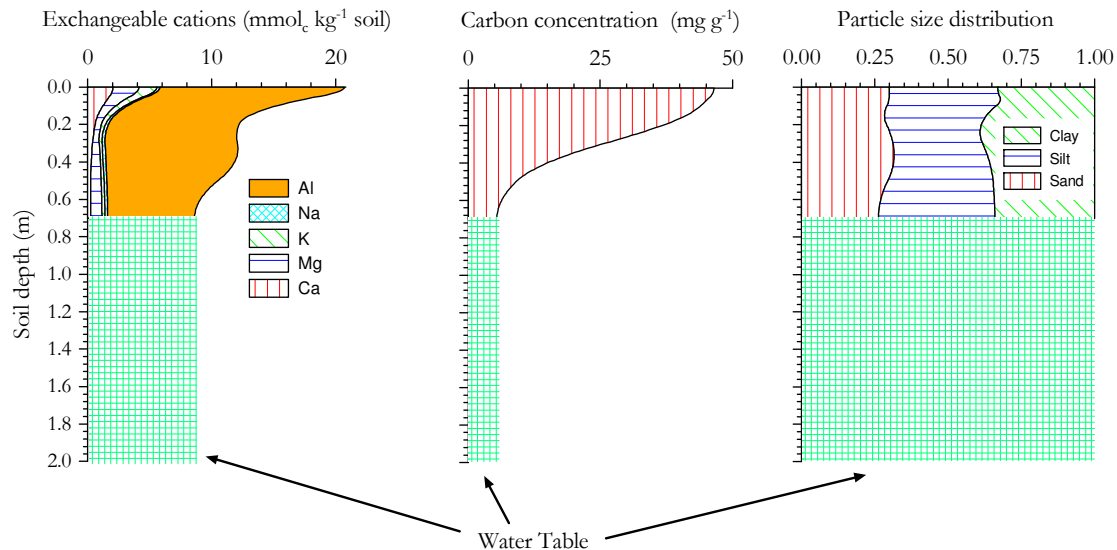


Fig. 17. Profiles of exchangeable cations, soil carbon and texture for a Endogleyic Umbrisol (Alumic, Hyperdystric) in Bolivia (LSL-01).

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀	▶
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	



The soils of
RAINFOR Project

C. A. Quesada et al.

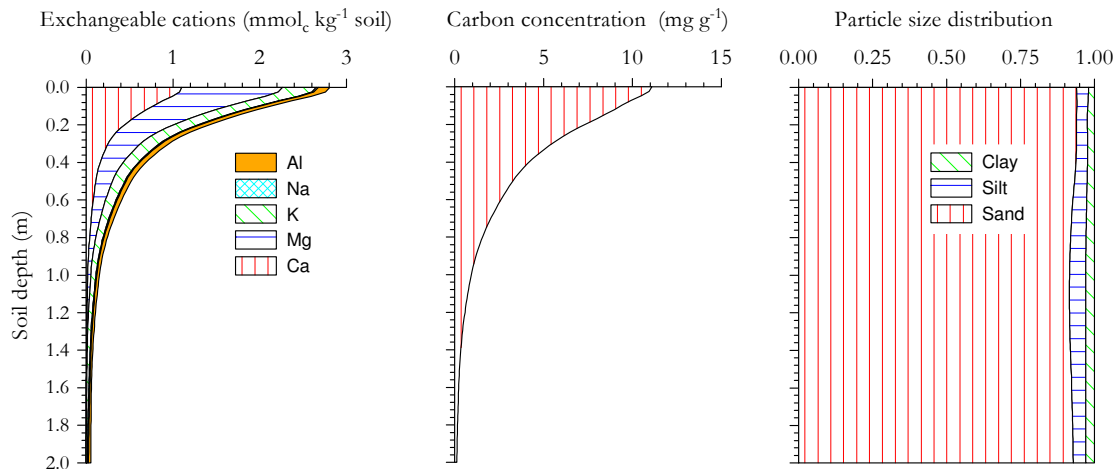


Fig. 18. Profiles of exchangeable cations, soil carbon and texture for a Haplic Arenosol (Hyperdystric) in North Peru (ALP-21).

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The soils of
RAINFOR Project

C. A. Quesada et al.

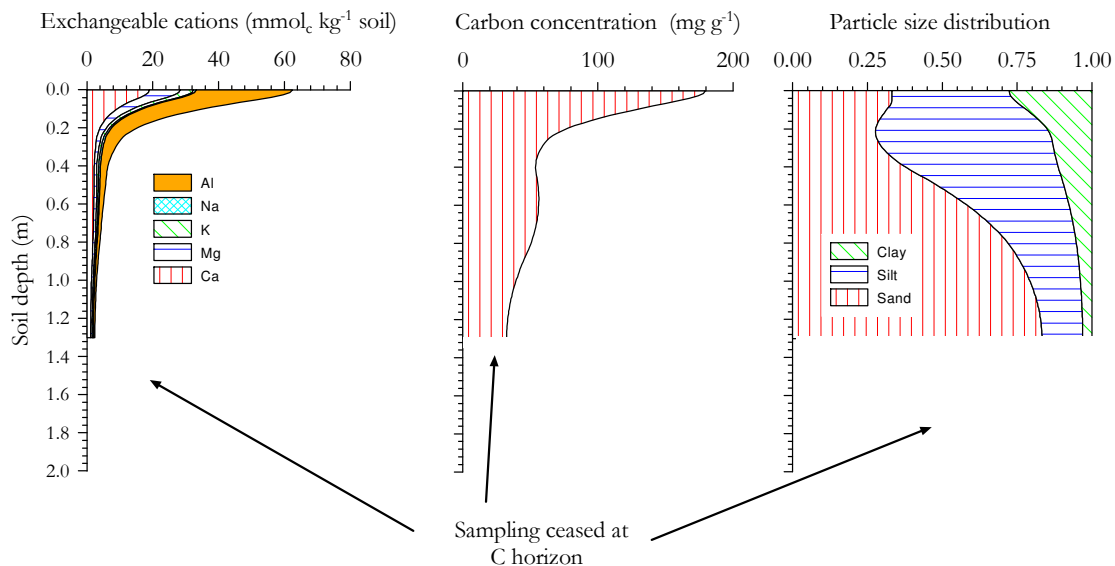


Fig. 19. Profiles of exchangeable cations, soil carbon and texture for a Silandic Andosol (Hyperdystric, Siltic) near the Sumaco volcano, Ecuador (SUM-06).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**The soils of
RAINFOR Project**

C. A. Quesada et al.

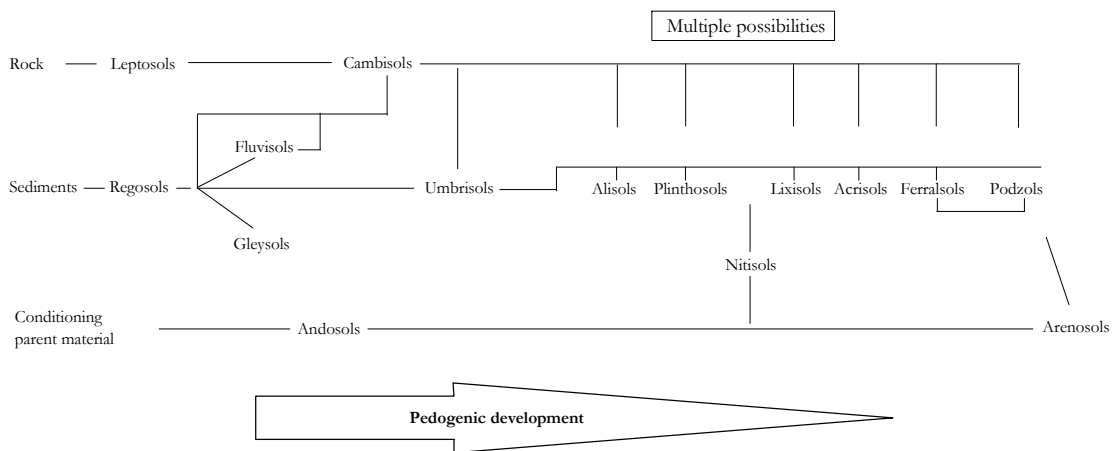


Fig. 20. Simplified scheme for soil development in Amazonia.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

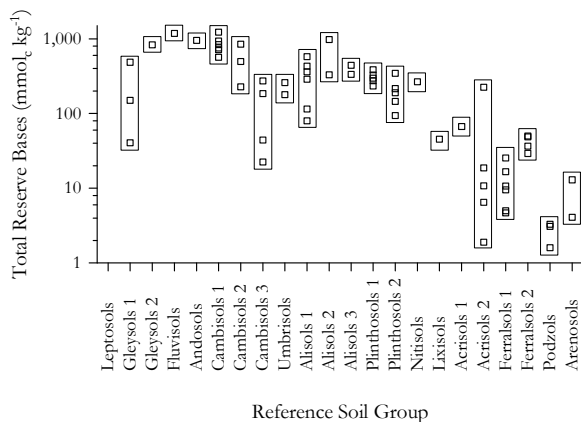
Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





RSG	Subgroup	Prefixes	Suffixes
Gleysols	1	Haplic	Hyperdystric Alumatic
Gleysols	2	Haplic	Orthoetric
Cambisols	1	Plinthic, Vertic or Haplic	Orthoetric
Cambisols	2	Stagnic or Vetic	Hyperdystric
Cambisols	3	Haplic	Hyperdystric Alumatic
Alisols	1	Haplic	Hyperdystric
Alisols	2	Hyperalic	Hyperdystric
Alisols	3	Haplic	Hyperdystric Alumatic
Plinthosols	1	Endostagnic	Hyperdystric Alumatic
Plinthosols	2	Haplic	Hyperdystric Alumatic; Orthodystric Alumatic
Acrisols	1	Vetic	Hyperdystric
Acrisols	2	Vetic	Hyperdystric Alumatic
Ferralsols	1	Geric	Hyperdystric Alumatic
Ferralsols	2	Geric Acric	Hyperdystric; Hyperdystric Alumatic

Fig. 21. Relationship between the axis of soil development and the chemically based weathering index Total Reserve Bases (Σ_{RB}). Details for World Reference Base lower level classification are also given.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

