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SOILS OF TROPICAL RAINFORESTS

Characterization and major constraints of dominant soils

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July 1995

ISRIC
INTERNATIONAL SOIL REFERENCE AND INFORMATION CENTRE

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SOILS OF TROPICAL RAINFORESTS

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ABSTRACT

Rational conservation and use of tropical forest resources should be based upon accurate knowledge of land and soil properties. Major soil groups of dominant (former) forest soils, covering 75% of the humid tropics, are characterized and their main limitations for agriculture are assessed. As representatives of the eco-region and on the basis of their presence in the ISRIC Soil Information System (ISIS) database, six major soil groups were identified: Ferralsols, Acrisols, Luvisols, Cambisols, Arenosols and Podzols. The selected 148 soil profiles are located in 20 countries throughout the humid tropics. Environmental conditions and soil properties were characterized and an assessment was made of the major constraints for low input, arable farming. Ferralsols, Acrisols, Arenosols and Podzols, covering a large extent of the humid tropics, present strict limitations to low input arable farming when forests are cleared. Overall data presented in this paper show that Ferralsols and Acrisols, together covering 60% of the humid tropics, have similar properties when considered for agriculture. When considering conservation of the natural vegetative cover and its biodiversity, several special properties of the soils have to be taken into account, such as the total rootable depth and the mineral composition of the deeper subsoil and the substratum, as well as the geomorphologic-pedologic history of the terrain units and the short-distance degree of variation in soil conditions. It is concluded that land assessment studies and soil-vegetation/biodiversity research should not rely on a soil taxonomic approach alone, but should also be based also on measured key properties.

1. INTRODUCTION

Tropical forests are being cleared at an unprecedented rate. Global deforestation rates are estimated at 15.3 million ha.y^{-1} for the period between 1981 and 1990. Deforestation of lowland moist rainforest, including moist deciduous forest, is estimated for the same period at 10.7 million ha.yr^{-1}, (FAO, 1995). Assessment and evaluation of land is the first step in rational use of forest resources on a sustained basis. For example, some land may best be left under forest to maintain an ecological balance because the combined limitations of climate, relief and soil make the land unsuitable for sustainable agriculture, while other areas may be capable of sustained intensive cropping. Other lands, in an intermediate situation, also should be kept under managed forest, or at least under forest fallow, to maintain ecological balance (Lal, 1987). Many soils of tropical rainforests are formed from geological materials in an advanced stage of weathering. After clearing, the infertility of the soils often poses considerable constraints to arable farming. The objective of the current study is to characterize major forest soils, covering 75% of the humid tropics, to assess their major limitations for agriculture, as well as their value for forest biomass production and its biodiversity. Rational use of forest resources should be based on accurate knowledge of land properties.

2. MATERIALS AND METHODS

2.1 National Soil Reference Collections and databases (NASRECs)

When the International Soil Reference and Information Centre (ISRIC) was established in 1966, its main task was to assemble soil profiles, soil samples and associated information representative of the legend units of the FAO-Unesco Soil Map of the World (FAO, 1974). Suitable sites were selected with the national institutions concerned. The main selection criterion was the representativeness of a major soil type within any particular country. Furthermore, specific soil and land use features were taken into account such as sites with original vegetation versus cleared land. At present, ISRIC's soil reference collection holds over 900 soils from 64 countries (ISRIC, 1992, 1995). Reference soils have a comprehensive set of soil and environmental data, some of which are published in a series of 'Country Reports' (e.g. ISRIC, 1994, 1995). Additional information on these reference soils is provided in a series of 'Soil Briefs'. Comprehensive information on reference soils accompanied by good quality data (based on standard methodologies) are becoming increasingly important for modelling at global or regional level, for instance in relation to climate change. Uniform datasets fulfil an essential role in the verification of heterogenous national datasets, in the development of pedotransfer functions as well as the testing and calibration of application programmes. The 1:5 million scale Soil Map of the World of FAO/UNESCO is known to be partly out-dated. In addition to FAO's own efforts, a long term effort to update the information on the world distribution of soils was initiated in 1986 with the World Soils and Terrain Digital Database (SOTER) project. It is being achieved in a series of regional projects executed by national soil institutions, supported by ISRIC, UNEP and FAO (Sombroek, 1984; Van Engelen and Wen, 1995).

The results of data from 148 reference soils in the humid tropics which are presented in this paper, form part of a correlation study for over 500 reference soils of the tropics and subtropics, which will be published later this year on the occasion of an international Workshop on National Soil Reference Collections and Databases (NASREC) in November 1995 (ISRIC, in prep.).

2.2 ISIS Dataset, field and analytical methods

Three soil pedon databases were developed at ISRIC, viz. ISIS (ISRIC Soil Information System), SOTER and WISE (World Inventory of Soil Emission Potentials). A review of these databases, and the possibilities of transfer between the databases is given by Batjes *et al.* (1994).

Data collected for ISRIC's soil reference collection are stored in the relational database management system ISIS (Van Waveren and Bos, 1988), which later formed the basis for developing the FAO-ISRIC Soil Database (FAO, 1989). Version 4.0 of ISIS is written in dBase IV and permits handling and analysis of:

- Site data, which include about 60 mainly descriptive (coded) attributes on location, geology, landform, soil surface properties, hydrology, land use and vegetation.
- Quantitative synoptic climatic data from meteorological stations that are considered representative for the conditions prevailing at the profile site.

- Profile data, including: i) soil profile descriptions mainly based on FAO guidelines ; ii) soil classification according to the legend of the FAO-Unesco Soil Map of the World (FAO, 1974 and 1988), USDA Soil Taxonomy (Soil Survey Staff, 1992) and the national system; and iii) physical, chemical and mineralogical attributes per soil horizon.

Chemical, physical and mineralogical data of ISRIC's world soil collection were determined by ISRIC's laboratory, using standardized analytical and quality assurance procedures (Van Reeuwijk, 1993). Soil horizons were described and sampled in soil pits of about 2 meters depth. Deeper soil layers were sampled using a soil auger to a maximum depth of 6 meters in some cases. In this paper most analytical results will be presented for a standardized thickness of topsoil and subsoil. If no specific depth range is given in the text, topsoil refers to the depth range from 0 to 20 cm, and for subsoil from 70 to 100 cm. Mean values are given for properties with a normal frequency distribution, and medians for skewed distributions.

The following key soil properties, frequently used in agricultural land use assessment and soil vegetation/bio-diversity research, were studied: i) chemical properties: soil reaction (pH-H_2O in 1 : 2.5 soil-water solution, and pH-KCl in 1 N KCl solution), organic carbon % (Walkley Black procedure), organic carbon/organic nitrogen (C/N ratio), sum of exchangeable bases, Cation Exchange Capacity (CEC, Ammonium acetate buffered at pH 7 procedure, in $cmol_c.kg^{-1}$), and base saturation as % of CEC. ii) physical properties: sand, silt and clay % (sieving and pipetting from a sedimentation cylinder), silt/clay ratio, bulk density, Rootable Pore Volume (RPV, calculated from pF 0 - pF 2.0, in vol. %) and Plant Available Moisture (PAM, calculated from pF 2.0 - pF 4.2, in vol. %). The pF or soil moisture retention data are obtained from undisturbed core samples equilibrated with water at various tension (pF) values. For details on the procedures see Van Reeuwijk (1993).

The effective, or 'rootable', soil depth was observed in the soil pits. Effective soil depth is very deep (> 2.0 m) for 90 % of the upland sites studied. For about 10 % of the soils, the effective depth ranges between 0.5 and 2.0 m. Rootable depth is limited by physical root barriers such as hard rock, hard pans, high permanent water table etc, or by chemical hindrance such as low content of one or more macro or micro nutrients, or toxic levels of exchangeable aluminium.

2.3 Ecological zones

The use of major climatic and soil-ecological zones for correlation of agricultural research is being promoted by several international agencies, such as the Food and Agriculture Organisation of the United Nations (FAO), the Consultative Group of International Agricultural Research (CGIAR), and the International Board for Soil Research Management (IBSRAM). ISRIC staff apply the concept of major ecological zones (FAO, 1978 - 1981) in projects such as NASREC and SOTER.

Currently ISRIC's world soil reference collection is being studied for 6 major global ecological zones mainly defined on the basis of climate: humid (sub)tropics, seasonally dry (sub)tropics, dry, highland, temperate and boreal regions. In this paper we only consider the humid (sub)tropics, being of interest to the theme of the conference. The following criteria are applied to select reference soil profiles from the database: altitude less than 1000 m, a humid or perhumid Length of Growing Period (LGP) between 270 and 365 days according to FAO (1978 - 1981) and an average monthly temperature over 18 °C throughout the year. This coincides broadly with Köppen's climate classes Af, Am and part of the Aw class with an annual precipitation of more than 1500 mm. The distribution of the humid tropics and subtropics, with 5 LGP classes, is shown in figure 1.

2.4 Distribution of ISRIC reference profiles over the humid tropical zones

Based on the criteria for the humid tropical zone mentioned before, 148 reference soils were selected for this study from the ISIS database. These soils originate from 20 countries and are distributed as follows: Brazil (7), China (3), Colombia (14), Costa Rica (10), Côte d'Ivoire (7), Cuba (5), Ecuador (4), Gabon (6), India (1), Indonesia (29), Jamaica (4), Malaysia (18), Nicaragua (4), Nigeria (10), Peru (11), Philippines (6), Samoa (3), Sri Lanka (1), Thailand (3) and Zaire (2). The locations of the profiles are well distributed throughout the humid tropical zone, although soils from Brazil and Zaire are under-represented.

Earlier overviews on the spatial variability of soil and landform conditions in the humid tropics, and an identification of research priorities are given in Van IJssel and Sombroek (1987) and Sombroek (1986) respectively.

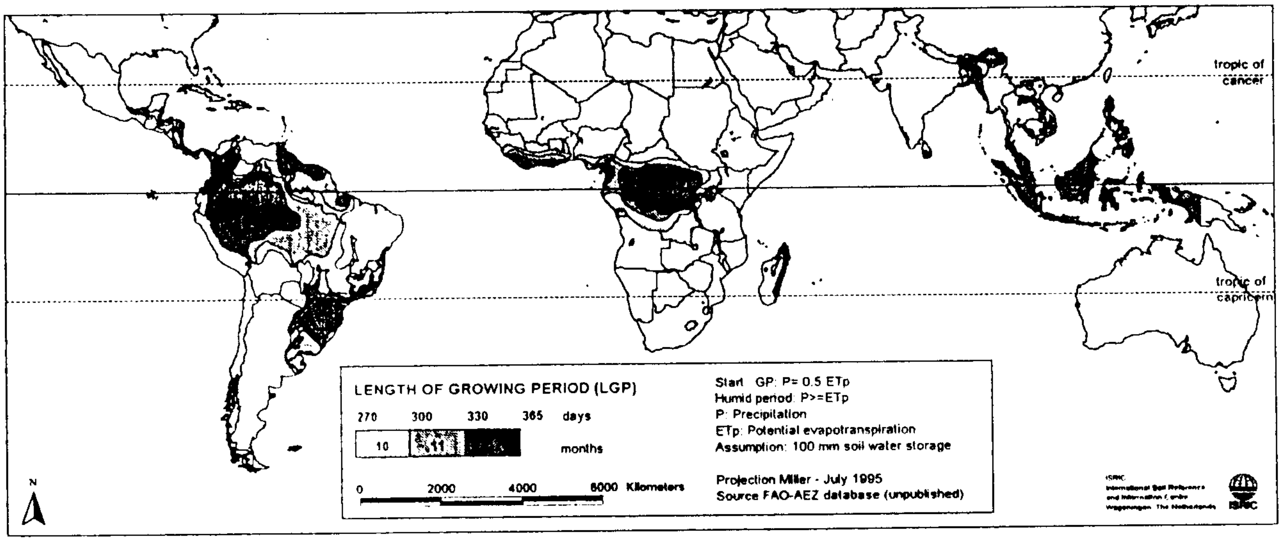

Figure 1: Distribution of the humid and perhumid zones of the tropics and subtropics.

3. RESULTS AND DISCUSSION

3.1 Soil Classification

Six major soil groups (FAO, 1974) are dominant in the database: Cambisols (22 %), Acrisols (22 %), Ferralsols (20 %), Luvisols (8 %) and Arenosols and Podzols together (11 %). Arenosols and Podzols are grouped in this study because both are characterized by sandy texture and usually occur in close spatial association in the humid tropics. Other major soil groups represented include: Andosols (6 %), Gleysols (5 %) , Fluvisols (4 %), but these three soil groups are not considered in this paper, because the number of reference soils is insufficient for statistical analysis. Compared to the revised FAO-Unesco Legend (1988) there are no major shifts for the five dominant soils, except that the Acrisols (FAO, 1974) include the Alisols (FAO, 1988) and Luvisols (FAO, 1974) include the Lixisols (FAO, 1988).
The representation of the six dominant soils of the humid tropics in ISRIC's database correlates well with the dominant extent of major soils groups in the climate zone 'Humid Tropics and Subtropics' as summarized in FAO's World Soil Resources (FAO, 1993, pag. 33). The six major soil groups cover approximately 75% of the total area of this climatic zone (in million hectares): Acrisols (589), Ferralsols (507), Gleysols (167), Arenosols and Podzols (138), Cambisols (95) and Luvi/Lixisols (53).
The most frequent subgroups of the six dominant soils are:

Ferralsols:	Xanthic (40%), followed by Acric and Orthic subgroups.
Acrisols:	Ferric (50%) with an equal distribution over Gleyic, Humic, Orthic and Plinthic subgroups.
Cambisols:	Ferralic (50%), followed by Dystric and Eutric subgroups.
Arenosols and Podzols:	no dominant subgroups

Similar area estimates, as found for the FAO-Unesco (1974) major soil groups, are expected from the World Reference Base for Soil Resources (Spaargaren, 1994), although, some shifts between major soil groups are anticipated. For example, a part of the Ferralic Cambisols will be included with the Ferralsols and part of the Ferralsols, showing a distinct clay increase be accommodated with the Acrisols. For further information on this subject see Spaargaren and Deckers (1995).

Soil classification according to international systems such as FAO (1988) and Soil Taxonomy (1994) is based on a limited number of characteristics used in the definitions of diagnostic horizons and properties, which allows uniform classification. Nonetheless, quantitative information on the variability of soil properties within each taxonomic soil group is scanty. The data available in ISIS are used to provide quantitative information on environment and soil properties of the six dominant soils, which in the remaining part of this paper are referred to as the 'dominant soils' of the humid tropical zone.

3.2 Ecological characterisation

In this section, general environmental characteristics of the sites are described including : precipitation, vegetation, parent material, landform and hydrology.

Precipitation

Precipitation at the 148 sites selected, ranges from 1400 to 4500 mm and exceeds evapotranspiration (ETp Penman) in most months. Leaching Rainfall (LR), which is calculated as the monthly excess of rainfall over evapotranspiration, ranges from almost 0 to 3000 mm with a mean of 1400 mm. LR is a parameter defined as the amount of water that potentially percolates through the soil to the zone below the roots and drains to the groundwater aquifer or laterally to a river system.

Vegetation

The original vegetation is mainly evergreen rainforest. About 25 % of the sites have a semi-deciduous forest. Rooting is in most cases very deep (see under 3.3; soil properties). The original vegetation has been cleared in about 70 % of the sites studied. Arable and grazing land are dominant land-use types for cleared land. Most frequently, the observed perennial crops were rubber, stimulants, fruit and oil trees. Common annuals were cereals and root, oil and protein crops.

Parent material

Information about 50 different types of observed parent material, underlying the described soils, is stored in the database. For soil fertility and soil genesis correlation purposes, this large variation of parent materials is pragmatically grouped according to composition in five categories. The frequency for the dominant soils are: acid (38 %), intermediate (12 %), basic (17 %), calcareous (7 %) and unconsolidated parent material (26 %). The unconsolidated materials include mainly alluvium and for a minor part colluvium and eolian sediments. The representation of the dominant soils in each compositional group:

Acid	all soil groups
Intermediate	Luvisols dominant
Basic	all soil groups, Ferralsols dominant
Calcareous	all soil groups
Unconsolidated	all soil groups, Acrisols, Cambisols and Arenosols/Podzols dominant

Landform

Over 30 landforms are described for the sites of the reference soils. This heterogeneity is summarized in four major relief categories with frequency % indicated: lowland alluvial and coastal plains (22 %); upland dissected and non-dissected plains (38 %); hills, including for a minor part plateaus (35 %); and mountains, including volcanoes (5 %).

Frequency of the topography classes described according to FAO (1988) at the site are: flat (26 %), undulating (38 %), rolling (17 %), hilly (10 %) and steep (10 %).

For sloping landscapes, the sites studied are situated principally on middle or upper slope positions. Less than 25% are located on a lower slope or crest position.

The dominant soils are represented in all landform, topography or position classes, except for the Arenosols/Podzols, which are found in flat to undulating alluvial or coastal plain situations.

Hydrology

Most of the dominant soil sites studied are well drained (70 %) or moderately well drained (20 %), followed by imperfectly (5 %) and (somewhat) excessively drained (5 %). In 95 % of the sites no groundwater table was observed, which corresponds with the upland position of the dominant soils.

3.3 Soil properties

A selection of key analytical properties, relevant for land use analysis and ecological research, is presented in this section and, where appropriate, correlated with field information. In table 1 the mean *(M)* or median *(Med)* values of the key analytical properties of the dominant soils in the humid tropics are given. Ranges are generally large for these properties. For additional information on standard deviation, upper and lower quartiles, see ISRIC (in prep.).

3.3.1 Physical properties

Particle size distribution

Five sand fractions have been determined by sieving, two silt fractions and one clay fraction by pipetting from a sedimentation cylinder. The sum of sand and silt fractions, and the clay fraction is presented in table 1.

Reflecting their sandy parent materials, Podzols and Arenosols have a very high sand content and a very low silt and clay content. Ferralsols, Acrisols, Luvisols and Cambisols have comparable clay content distributions. For these soils a correlation of clay content with parent material composition is more striking. The mean clay content of soils formed on acid parent materials is 23 %, compared to 58 % for basic materials. Ferralsols, dominantly derived from basic parent materials, therefore have slightly higher clay contents than the other major soil groups.

A distinct increase in clay content between topsoil and subsoil, is not a manifest feature of the dominant soils of the humid zone. The most pronounced increase is found in Acrisols, with a mean clay increase of 11 % in the first meter of the soil. Although for the Acrisols in the world-at-large the increase takes place over a shorter depth range, such a gradual increase of clay content in the Acrisols of the humid tropics will have only limited influence on e.g. root development and soil hydraulic properties. This is also evidenced by the field morphology, where horizon boundaries are usually gradual or diffuse, caused by bio-homogenization.

Table 1 - Key analytical properties of dominant soils in humid tropics.

		TOPSOIL (0 - 20 cm)					
		FERR	ACRI	LUVI	CAMB	AREN	PODZ
Sand (%)	*(M)*	35	52	40	25	92	86
Silt (%)	*(M)*	15	19	20	27	5	11
Clay (%)	*(M)*	49	29	35	46	3	3
Silt/Clay	*(M)*	0.4	0.9	0.6	0.9	5.1	5.6
Bulk density (g.cm^3)	*(M)*	1.1	1.3	1.2	1.1	1.2	1.3
Rootable pore volume (%)	*(M)*	16	13	16	14		
Plant avail. moisture (%)	*(M)*	12	14	14	17		
pH-H$_2$O (1:2.5)	*(M)*	4.8	4.8	6.4	5.3	5.3	4.5
pH-KCl (1:2.5)	*(M)*	4.1	4.1	5.5	4.5	4.1	3.7
Organic Carbon (%)	*(Med)*	1.9	1.7	2.0	2.0	0.8	1.4
C/N ratio	*(M)*	16	14	17	11	16	23
Sum of bases (cmol$_c$.kg^{-1})	*(Med)*	0.8	1.7	16.0	3.1	1.0	0.5
Exch. Al (cmol$_c$.kg^{-1})	*(Med)*	0.8	1.1	0.0	0.1	0.0	0.1
CEC$_{pH7}$ (cmol$_c$.kg^{-1})	*(Med)*	7.8	6.4	16.7	15.2	4.4	4.0
Base Saturation (%)	*(Med)*	13	19	94	28	22	13

		SUBSOIL (70 - 100 cm)					
		FERR	ACRI	LUVI	CAMB	AREN	PODZ
Sand (%)	*(M)*	29	36	30	26	95	85
Silt (%)	*(M)*	15	19	21	25	1	8
Clay (%)	*(M)*	52	40	40	40	3	7
Silt/Clay	*(M)*	0.3	0.6	0.5	0.8	0.5	1.2
Bulk density (g.cm^{-3})	*(M)*	1.2	1.4	1.3	1.2	1.4	1.5
Rootable pore volume (%)	*(M)*	15	9	8	13		
Plant avail. moisture (%)	*(M)*	11	12	13	16		
pH-H$_2$O (1:2.5)	*(M)*	5.0	4.8	5.9	5.4	5.8	4.8
pH-KCl (1:2.5)	*(M)*	4.5	4.0	4.6	4.5	5.1	4.4
Organic Carbon (%)	*(Med)*	0.4	0.4	0.4	0.3	0.3	0.2
C/N ratio	*(M)*	9	8	7	8	12	31
Sum of bases (cmol$_c$.kg^{-1})	*(Med)*	0.3	0.4	4.7	3.6	0.5	0.0
Exch. Al (cmol$_c$.kg^{-1})	*(Med)*	0.2	1.9	0.0	0.0	0.0	0.1
CEC$_{pH7}$ (cmol$_c$.kg^{-1})	*(Med)*	3.0	5.1	5.0	9.1	0.8	1.4
Base Saturation (%)	*(Med)*	9	7	89	52	32	1

(*(M)*=Mean *(Med)*=Median).

(FERR = Ferralsols, ACRI = Acrisols, LUVI = Luvisols, CAMB = Cambisols, AREN = Arenosols, PODZ= Podzols).

The silt fraction is relatively low in soils of the humid tropics, and is lowest in Ferralsols and highest in Cambisols. This is also reflected in the silt/clay ratio. This ratio is 0.3 in subsoils of Ferralsols and double for the other major soil groups. In the revised legend (FAO, 1988) a silt/clay ratio of < 0.2 is introduced as a diagnostic criterion in the classification of Ferralsols. When rigidly applied, a large part of the 1974 Ferralsols cannot be classified as such in the revised legend. In view of the difficulty to disperse tropical soils before measuring the silt and clay fractions it is recommended that further investigation of the applicability of the silt/clay ratio take place.

Bulk density, rootable pore volume and plant available moisture

The results of bulk density, potential Rootable Pore Volume (RPV) and potential Plant Available Moisture (PAM) for the dominant soils are presented in table 1.

The mean bulk density of topsoils of the humid tropics is low (1.1 - 1.3 $g.cm^{-3}$) but subsoils approach the average values found elsewhere. There are no large differences comparing the major soil groups, but Ferralsols have the lowest and Acrisols have the highest mean bulk density. The rootable pore volume for topsoils is comparable for the dominant soils. Acrisols are lower with 13 % rootable pore volume, but this is considered not to be limiting for root development in their topsoils. Large differences are found in the subsoil when comparing Ferralsols and Cambisols, with a high potential rootable pore volume and Acrisols and Luvisols with a lower rootable volume. Possible explanations for this are: i) the occurrence of illuviation of clay and the formation of clay skins on structural elements in Acrisols and Luvisols; ii) Ferralsols have more stable micro-aggregates and biopores. In addition Acrisols and Luvisols possibly have less bio-activity in the subsoil, but this could not be inferred from the field descriptions.

The Plant Available Moisture (PAM) data of the dominant soils show no large differences between topsoil and subsoil. Expectedly, values are slightly higher for the topsoil, which can be explained by a better structure. Cambisols show the highest potential PAM and Ferralsols the lowest, with Acrisols and Luvisols taking an intermediate position. Dry periods are relatively short in the humid zone, if present at all; therefore, none of the mean PAM values are a constraint for crop production. The situation may be different for forest growth or re-growth (see 3.5).

3.3.2 Chemical properties

Soil reaction

Soil reactions, pH-H_2O and pH-KCl, of the dominant soils range from extremely acid to neutral. The mean values are given in table 1. Ferralsols, Acrisols and Arenosols soil groups have similar ranges and are predominantly acid. Except for the Luvisols, the dominant soils have a comparable soil reaction in topsoil and subsoil; the pH-H_2O levels of the topsoils are similar or slightly lower than in the subsoils.

A measure for the net charge status of the soil is delta pH, referring to the difference between pH-KCl and pH-H_2O. Ferralsols have a mean delta pH of -0.7 pH unit and the other soils around -1.0 pH unit (net negative charge: CEC). A histogram of the delta pH for all soil samples shows that a positive delta pH is rare in this set of data (see figure 2). This applies also to the Ferralsols, which frequently are considered to have a positive delta pH (net positive charge: AEC).

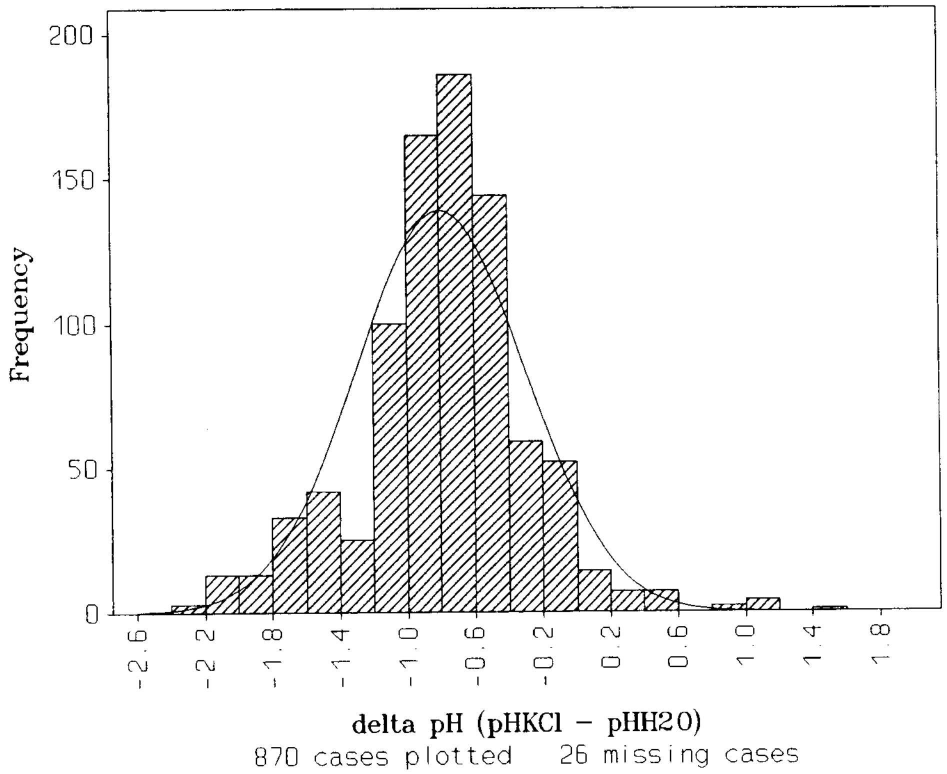

Figure 2: Delta pH histogram of 148 reference soils of the humid tropics.

Extractable aluminium

In general, the extractable aluminium content is negligible when pH-$H_2$0 exceeds 5.5 (which corresponds to a pH-KCl > 4.8), as free aluminium is neutralized. Soils with pH values below these levels can have a high level of extractable aluminium, inducing Al-toxicity for rootgrowth.

A correlation of pH-KCl and aluminium saturation for all soil samples is presented in a scatterplot (figure 3). Additional information on extractable aluminium is given in section 'nutrients'.

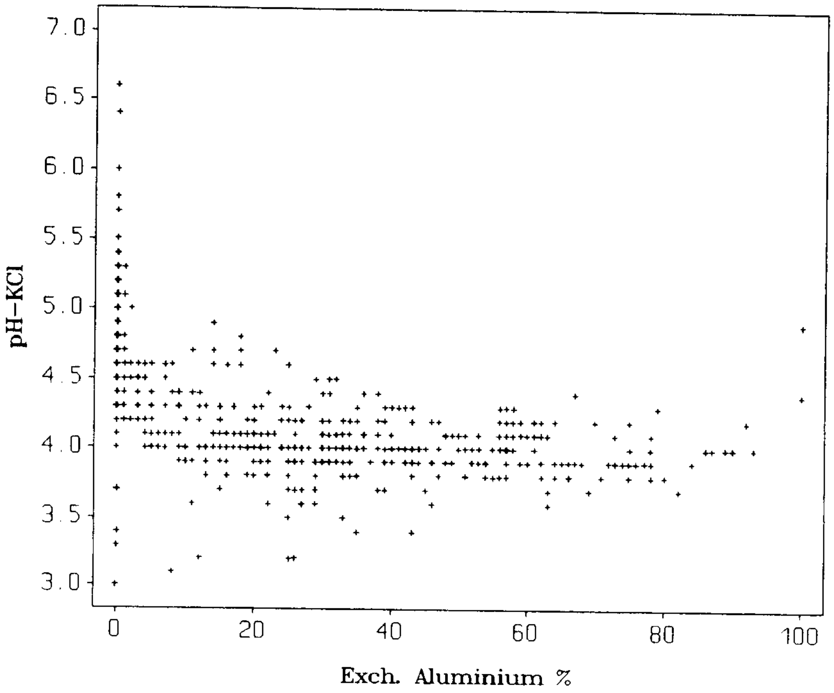

Figure 3: Scatter plot of pHKCl vs Al-saturation % using 148 ref. soils of the humid tropics.

Organic Carbon

Information about soil organic matter is presented as organic carbon. A plotting of organic carbon content with depth of all samples shows an expected highest level of organic carbon in the upper 50 cm of the soil profiles, but also substantial amounts are found in the deeper subsoil of some soils (figure 4). The organic carbon content and C/N ratio of topsoil and subsoil for each dominant soil is presented in table 1.

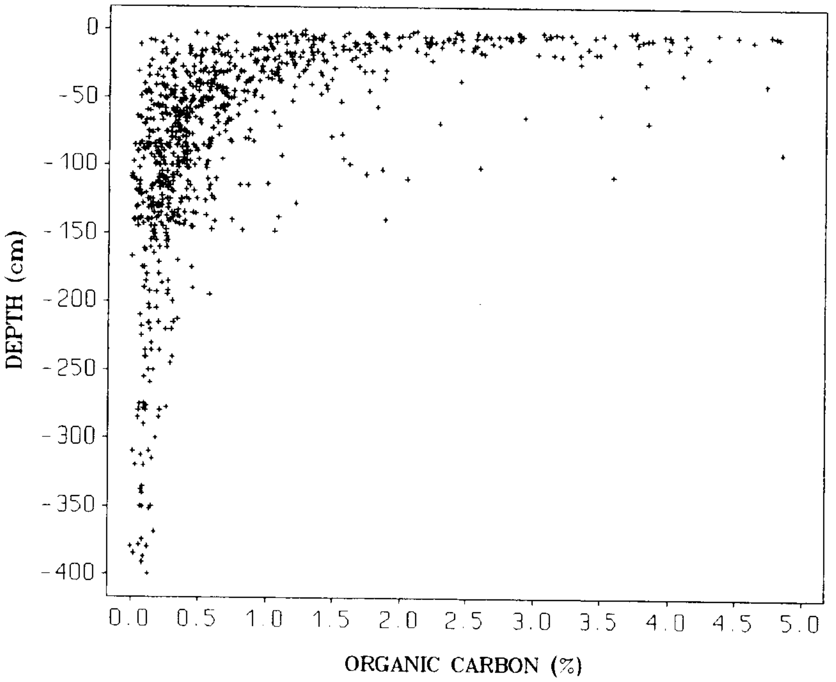

Figure 4: Scatter plot of organic C vs depth of 148 reference soils from the humid tropics.

Ferralsols, Acrisols, Luvisols and Cambisols have a comparable distribution of organic carbon within their profiles. Arenosols and Podzols clearly form a separate group with a much lower organic carbon level. However, some subsoil horizons of individual soil profiles have a much higher level, associated with the presence of a podzol B horizon (i.e. an accumulation of organic material and iron in the subsoil, partly as an indurated layer ("ortstein"). In the humid tropics, the podzol B horizon may be situated at a great depth).
Contrary to the general expectation, organic carbon also accumulates in the subsoils of the humid tropics (figure 4). The organic carbon content of the soils can be 1 % at a depth of 50 cm, and 0.5 % at a depth of 100 cm. Comparing field descriptions and analytical data of soils from several countries (e.g. from Brazil and Indonesia), it is observed that such relatively high organic carbon levels in the subsoil are not matched by a darker soil matrix colour. These subsoils have clear yellowish or reddish soil matrix colours, with Munsell color codes of hue 5 to 10 YR and value/chroma combinations of 4/5 to 6/8, which outside tropical areas are indicative of a much lower level of organic carbon. The accumulation of organic carbon in the deeper subsoil and its importance for plant available water, nutrient retention, etc. is also reported from deeply weathered clay soils (Xanthic Ferralsols) in the states of Pará and Amazonia, Brazil (Nepstad *et al*, 1994). Therefore analysis of organic carbon content of the deeper subsoil, irrespective of observed soil matric colour, is advocated.

The degree of decomposition (or mineralisation) of organic matter is characterized by the C/N ratio. High C/N ratios are indicative for a low degree of decomposition and low values for a high degree of decomposition. The mean C/N ratios for the dominant soils are presented in table 1. The overall difference of the C/N ratio between topsoil and subsoil is large. This may be explained by a better decomposition of organic matter with depth and age. In addition, transport of the more decomposed, finer, organic fraction from the topsoil to the subsoil may contribute to this difference. However, the influence of the latter can not be large, because of the pronounced bio-homogenisation. Ferralsols, Acrisols, Luvisols and Cambisols have comparable low C/N ratios in the subsoil. Cambisols have the lowest C/N ratio in the topsoil, indicative of good quality organic matter. High C/N ratios indicate that organic matter in Podzols and Arenosols is less decomposed; especially in Podzols the C/N ratio is very high, which is a reflection of the poor parent material of the soil and poor quality of organic materials. No correlation is found between organic carbon content and soil reaction for acid soils ($pH\text{-}H_20 < 5.5$), at any depth, nor is a correlation with the extractable aluminium content apparent. The correlation of organic carbon content with parent material has been studied also. For soils derived from acid parent materials the mean organic carbon content of the topsoil is 0.8 % less than that of soils developed on basic parent materials.

Nutrients
In addition to the soil reaction and soil organic carbon content, the nutrient status of the soil is further characterized by the exchangeable bases (calcium, magnesium, potassium and sodium), the extractable acidity (hydrogen and aluminium), and the measured cation exchange capacity (CEC) at pH 7. The mean values for each dominant soil are presented in table 1.

Mean values for the sum of exchangeable bases, cation exchange capacity and base saturation, of topsoil and subsoil are low or very low for Ferralsols, Acrisols, Arenosols and Podzols. Cambisols and Luvisols form a separate group with moderate to high values.

There is no good correlation between the sum of the bases and the five parent material classes. Generally, soils developed on basic parent materials have a slightly higher CEC, sum of bases, and base saturation compared with acid, intermediate or old alluvial parent materials.

The extractable aluminium content of Acrisols and Ferralsols is high, and nil or very low for the other dominant soils. The absolute value of extractable aluminium is low in the subsoil of the Ferralsols. However, the mean aluminium saturation expressed as percentage of the ECEC is high, about 50 % and comparable with Acrisols (the ECEC is calculated from the sum of exchangeable bases and exchangeable acidity and is considered to approximate the actual nutrient retention of the soil under field conditions).

3.3.3 Mineralogical properties

The mineralogical composition of the 148 reference profiles, as determined by X-ray analysis of the clay fraction, gave a strong predominance of kaolinite, with varying percentages of iron- and aluminium oxides (hematite, goethite, gibbsite, etc.) related to the colour of the soils. The Luvisols and Cambisols had various amounts of illite, kaolinite and mixed layered silicate clays.

The mineralogic composition of the fine sand fraction was carried out only for a few of the reference soil profiles. There are indications (Sombroek, 1990) that the amount and composition of non-quartz minerals of the sand fraction in the subsoils and the underlying substratum are a determinant for the species diversity in tropical forests. However for a systematic verification many more observations are needed, both on the mineralogy of the soils and the species composition of the forest growing on it.

3.4 Major agronomic constraints

For the purpose of highlighting major soil/land constraints for agriculture, a qualitative evaluation of 15 land qualities was made. The land qualities and the methodology are based on the Framework for Land Evaluation (FAO, 1976, 1983). The land quality assessment is generally based on 2 or more single land characteristics. Critical values and other class limits for single soil parameters are adapted from several publications, e.g. Ilaco (1981) and Landon (1984). To make the assessment applicable for all tropical regions, criteria have been developed for a deep rooting annual crop, assuming low technology and low inputs. In 'Framework' terms this corresponds with a major kind of land use, viz. "rainfed agriculture, annual cropping". Each land quality is rated in 5 classes and indicates the degree of limitation for the specified use.

Rating procedures have been computerized with the Automated Land Evaluation System (ALES), (Rossiter and Van Wambeke, 1993), to make an assessment of the present status of the land using the reference soils. Depending on the type of land quality, an assessment is made for a specific depth range. For soil surface characteristics the first soil horizon is evaluated; for nutrient status related characteristics it is assessed over 0 - 50 cm, and for others over the depth 0 - 120 cm. Frequencies of the five degree classes for the dominant soils are expressed in percentages in table 2.

The assessment should not be regarded as an absolute judgement but rather as a first identification of constraints for agriculture.

Table 2 - Frequency (%) of constraints by land quality of grouped dominant soils.

degree of constraints land quality	no	weak	moderate	serious	very serious
length of growing period	70	30	0	0	0
drought hazard	100	0	0	0	0
soil moisture availability	5	39	36	13	6
oxygen availability	68	18	6	7	1
nutrient availability	2	9	13	33	43
nutrient retention capacity	7	5	12	38	38
rootable volume	58	29	10	3	0
conditions for germination	97	2	1	0	0
salinity	99	0	1	1	0
sodicity	79	7	7	1	6
aluminium toxicity	24	0	33	13	30
workability	21	57	15	7	0
potential for mechanisation	38	22	19	16	5
resistance to erosion	41	28	10	11	9
flooding hazard	77	14	8	0	1

The qualitative degree of limitation reads as follows:

no = no constraint or limitation, no yield reduction
weak = slight limitation, little yield reduction
moderate = moderate limitation, some yield reduction
serious = severe limitation, clear yield reduction
very serious = very severe limitation, strong yield reduction or no yield.

Because of rounding, the sum of percentages for each land quality may sum to 99 or 101.

Major constraints for dominant soils of the humid tropics are: a low level of plant nutrients, a low level of nutrient retention capacity, and toxicity caused by high extractable aluminium level.

Each dominant soil was evaluated for the land qualities indicated in table 2. Then, for each dominant soil, the median of the land quality ratings (1 = no limitation to 5 = severely limiting) was calculated. In table 3, the major limitations (those that were moderately or (very) severely limiting for at least one soil type) are given for the dominant soils.

Table 3 - Major limitations of dominant soils of the humid tropics

land quality	Ferr	Acri	Luvi	Camb	Aren/Podz	All
Soil moisture	+	+	+		+++	+
Nutrient availability	+++	+++		++	+++	++
Nutrient retention	+++	++	+	++	+++	++
Aluminium toxicity	++	++		+	+	+
Mechanisation			+			
Resistance to erosion			+			

(+ = moderately limiting, ++ = severely limiting, +++ = very severely limiting.)
(Ferr = Ferralsols, Acri = Acrisols, Luvi = Luvisols, Camb = Cambisols, Aren = Arenosols, Podz = Podzols and All = overall figure of 6 soils).

From this table it can be seen that of the five dominant soils, Luvisols have the most favourable properties for agriculture. Cambisols have severe limitations for availability and retention of nutrients and are moderately aluminium toxic. Ferralsols and Acrisols have comparable limitations: (very) severe limiting nutrient retention and nutrient availability, severely aluminium toxicity and moderate soil moisture retention.

3.5 Relationships between soil properties and the characteristics of the natural vegetative cover

Soil properties strongly influence the characteristics of the forest growing on it. However, there are few strictly paired observations across the three continents concerned on soil conditions and the local structure of the natural vegetation -multistorey closed-canopy forest *vs* open-canopy forest *vs* savanna-forest-, its total timber volume and biomass, including Carbon storage, and its biodiversity.

In overview papers on these relationships for the Amazon region (Sombroek, 1990, 1992) it was concluded that the highest gross timber volumes (over 200 $m^3.ha^{-1}$) are found in those areas where the total annual rainfall is not excessively high (less than 3000 mm per year); where a short relatively dry season exists (less than four consecutive months with lower than 50 mm rainfall each) and where moreover the soils are deep (more than 200 cm) and well drained, not very sandy and lacking a compact subsoil. Such soils, with a substantial effective soil moisture storage capacity, are mainly of the Xanthic Ferralsol type as predominant in the eastern axial part of the Amazon basin. If the dry season is too strong, and/or the soils are less deep or having somewhat compact subsoil (such as the Acrisols in part of the fringe areas of the Amazon region), then an open-canopy forest prevails of lower biomass and with a larger propensity for degradation into bamboo-, liana- or savanna vegetation under early or presentday anthropogenic influences such as shifting cultivation.

Arenosols, Podzols, Plinthisols, dystric Gleysols and Histosols have already naturally a forest of low timber volume ("caatinga Amazonian"), tree savanna vegetation with bare white-sand patches ("campina"), scrubby to open grass savanna ("campo"), or a strong predominance of palm species. Such patterns are also known for the Zaire basin and Borneo.

The relationship between soil conditions and the biodiversity of the natural vegetative cover are more complex. This is linked with the various aspects of biodiversity: species diversity, endemism and speciation. The *richness in species* of a range of habitats in the geographic unit under consideration ("gamma" biodiversity) is bound to be highest in areas with short-distance strong variation in habitat, where the landscape is composed of land facets of strongly different topographic, soil, hydrological and microclimatic conditions. These areas are to be found in uplands and hilly areas where geomorphological processes were active in several episodes of the Pleistocene or Early Holocene, especially where such activity resulted in exposure of fresh rocks or sediments of short-distance contrasting lithology and mineralogy. Hilly lands and uplands with convex slopes over crystalline basement or older sedimentary rocks are, therefore, likely to have the highest degree of species richness.

Endemism, or the restriction of species to specific areas within the biome is often linked to extreme climatic, hydrologic or soil conditions, where such species have a competitive advantage. For the Amazon region this applies, for instance, to the species Cedro (*Cedrela odorata*), Mahogany (*Swietenia macrophylla*) and Castanhado-Pará (*Bertholetia excelsa*).

The "campina" and "caatinga" units on the Arenosols and Podzols of the Amazon have a well-documented low degree of species richness but a high number of endemic species. This is also reported for other areas with such kind of soils, such as parts of Borneo.

Even in areas with seemingly monotonous cover of well drained, strongly weathered non-sandy soils such as Ferralsols and with identical climatic conditions there are phyto geographic differences. This holds, for instance, for the occurrence of Angelim-pedra (*Hymenolobium excelsum*) and Pau-amarelo (*Euxilophora paraensis*) on only some landscape facts of eastern Amazonia; in both cases a specific micro-nutrient content of the substratum is surmised to be the determining factor (Sombroek, 1990).

Large *intra-specific variation* and the evolution of new species, as forms of genetic diversity, are supposed to occur where past climatic, geomorphologic and soil conditions were not much different from those of today ("refuge" areas). For the Amazon region, such areas have tentatively been identified as isolated sandstone table-lands, in fact high-level sedimentary plains of the Late Tertiary - Early Pleistocene age (the Amazon "planalto"), and areas of relic valleys with long concave slopes.

To accurately assess the high biodiversity values, multidisciplinary terrain studies are needed on the geographic relationships between floristic species occurrence, soil conditions, historic stability of landscapes, past climatic conditions and past anthropologic influences (the latter may have contributed to bio-diversity as well!). Full or partial protection of forest areas of the upper part of hydrological catchments, of areas with unstable or otherwise fragile soils, and of areas of indigenous forest dwellers, has to go hand-in-hand with protection of proven high-biodiversity forests, through a process of holistic (agro-) ecologic and (socio-) economic zoning and subsequent land use or non-use planning, the latter in close cooperation with all the stakeholders on the future of the tropical forest lands.

4. CONCLUSIONS

A large extent of the humid tropics is covered by Ferralsols, Acrisols, Arenosols and Podzols, all presenting various degrees of limitations when forests are cleared for (low input) arable farming. Cambisols and Luvisols have much less limitations.

Arenosols and Podzols can easily be distinguished from the Ferralsols and Acrisols on the basis of their key properties. The overall data presented in this paper show that Ferralsols and Acrisols, covering 60 % of the humid tropics, have rather similar key properties. The separation is based on a relatively small increase in clay content, which will not determine the major vegetation type or crop productivity level. These conclusions tally with the results obtained in recent research in the Colombian Amazon (Duivenvoorde and Lips, 1995). On the other hand variability of each key property for both Ferralsols and Acrisols is large. Agricultural land assessment studies and soil vegetation/bio-diversity correlation studies should be based on measurements of key soil properties, reflecting the bio-physical functioning of the soil, and should not rely only on a soil taxonomic approach.

In view of the very low to low nutrient content of top and subsoil, the determination of the decomposing organic materials covering the mineral soil as the litter layer, being the main source of soil fertility in the studied dominant soils, should be included as a potential key property.
The topsoil classification of FAO (1992) may also contribute to an improved assessment of the soil fertility status, because initial testing in West Africa shows its potential (Hebel *et al.*, 1994).

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