SEÇÃO V - GÊNESE, MORFOLOGIA E CLASSIFICAÇÃO DO SOLO

EVALUATION OF MORPHOLOGICAL, PHYSICAL AND CHEMICAL CHARACTERISTICS OF FERRALSOLS AND RELATED SOILS[1]

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SUMMARY

Morphological, physical and chemical data of 58 soil profiles of Ferralsols and low activity clay Cambisols, Lixisols, Acrisols and Nitisols and of Alisols of the International Soil Reference and Information Centre (ISRIC) collection, described and sampled in eighteen different countries of tropical and subtropical regions, were selected to analyse their consistency and, or, variability and to search for properties to better describe and differentiate them. The soil profile descriptions were based on the guidelines of FAO and the FAO endorsed analytical methods of ISRIC. Frequence diagrams of the data show an asymmetric positively skewed and leptokurtic distribution for sand and silt fractions, specific surface, exchangeable bases and cation exchange capacity. Clustering soil colour hues, values and chromas rendered four distinct clusters, respectively of Rhodic, Rhodic/Xanthic (Haplic), Xanthic and Humic properties. The same technique applied to particle size distribution also originated four clusters, respectively of fine loamy, fine silty, clayey and fine clayey soils. Most of the soils analysed are acid, with low base saturation, except for Rhodic Nitisols and Rhodic Ferralsols, which present low exchangeable aluminium. Higher and variable values of this property are found in the other soil classes studied. Cation exchange capacity is also low and related to the kaolinitic and oxihydroxydic composition of the clay material. Regression analysis applied to cation exchange capacity resulted in low correlations with clay and silt content and higher with organic carbon and specific surface and clay content.

Index terms: tropical soils, low activity clay soils, acid soils, low exchangeable bases.

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RESUMO: *AVALIAÇÃO DE ATRIBUTOS MORFOLÓGICOS, FÍSICOS E QUÍMICOS DE FERRALSOLOS E SOLOS RELACIONADOS*

A morfologia e os dados de análises físicas e químicas de 58 perfis de Ferralsolos e de Cambissolos, Lixissolos, Acrissolos e Nitissolos de argila de atividade baixa e de Alissolos, da coleção do International Soil Reference and Information Centre - ISRIC, descritos e amostrados em dezoito países tropicais e subtropicais, foram utilizados não só para analisar a consistência e, ou, variabilidade destes dados, mas também para pesquisar características que possam melhor descrevê-los ou diferenciá-los. A descrição dos perfis de solos seguiu as normas da FAO e os métodos analíticos do ISRIC, endossados pela FAO. Em diagramas de freqüência, os dados mostram uma distribuição assimétrica com inclinação positiva e leptocúrtica para teor de areia e silte, superfície específica, bases trocáveis e capacidade de troca de cátions. Análise de conglomerados aplicados à matiz, valor e chroma da cor dos solos, originou quatro agrupamentos distintos, respectivamente, de solos vermelhos, vermelho-amarelos (háplicos), amarelos e húmicos. A mesma técnica aplicada à distribuição do tamanho de partículas também originou quatro agrupamentos, respectivamente, de solos franco-argilosos, siltosos, argilosos e muito argilosos. Os solos estudados são ácidos, de baixa saturação por bases, com exceção dos Nitissolos ródicos e Ferralsolos ródicos, que apresentam baixa saturação por alumínio; contudo, valores mais elevados e variáveis para este atributo são encontrados nas demais classes de solo estudados. A capacidade de troca de cátions é baixa e relacionada com a composição caulinítica e oxiidroxídica da fração argila. Análise de regressão aplicada à capacidade de troca de cátions resultou em baixas correlações com teor de argila e silte, mas maiores com carbono orgânico e entre superfície específica e teor de argila.

Termos de indexação: solos tropicais, solos com argila de atividade baixa, solos ácidos, solos com bases trocáveis baixas.

INTRODUCTION

As defined in the Revised Legend of the Soil Map of the World (FAO, 1988), Ferralsols are soils having a ferralic B horizon, which is a subsurface horizon that: (a) is at least 30 cm thick, (b) has cation-exchange capacity (CEC) ≤ 16 $cmol_c$ kg^{-1} clay or an effective cation exchange capacity (ECEC) ≤ 12 $cmol_c$ kg^{-1} clay (sum of NH_4OAc-exchangeable bases plus 1 mol L^{-1} KCl-exchangeable acidity), (c) < 10% weatherable minerals in the 50-200 mm fraction, (d) texture that is sandy loam or finer and has at least 8% clay in the fine-earth fraction, (e) < 10% water-dispersable clay, (f) < 5% by volume showing rock structure, (g) a silt/clay ratio ≤ 0.2 and, (h) does not have andic properties.

Apart from some minor conceptual differences, this soil class corresponds to the Oxisols of Soil Taxonomy (SCS/USDA, 1975, 1997); Latosols of the soil classification as used in the Brazilian soil surveys (Camargo et al., 1987) and the Brazilian system of soil classification (EMBRAPA, 1999); Krasnozems of the Australian soil classification system (Isbell, 1977); Ferralsols of the world reference base for soil resources (ISSIS Working Group RB., 1998ab) and Ferralitic soils (Duchaufour, 1963) in the French systems.

Not considering details in the concepts defined in FAO (1988), Cambisols are soils having a cambic B horizon and no diagnostic horizons other than an ochric or an umbric A horizon or a mollic A horizon overlaying the cambic B horizon with base saturation < 50%. Lixisols and Acrisols have an Argic B horizon with cation exchange capacity of less than 24 cmo_c kg^{-1} clay, but the former have a base saturation > 50% and the latter < 50%. Nitisols have an argic B horizon with a clay distribution which does not show a relative decrease from its maximum of more than 20% within 150 cm of the surface, gradual to diffuse horizon boundaries and nitic properties in some subhorizon within 125 cm of the surface. Alisols have also an argic B horizon, but with cation exchange capacity ≥ 24 cmo_c kg^{-1} clay and a base saturation < 50% in at least some part of the B horizon within 125 cm of the surface.

Ferralsols are strongly weathered soils found on old geomorphic surfaces, covering extensive areas in the tropical region of South America and Africa and minor ones in Asia, Australia and Central America. Some of these regions are still sparsely populated because of natural soil infertility, but they represent possibilities for the expansion of agricultural areas, mainly due to their suitable climatic and topographic conditions for crop production. At the same time it is recognized that many of these soils are under pristine tropical rain forest, a most valuable natural resource.

Because of their occurrence in tropical regions, where generally the development of scientific investigation has not reached the level found in temperate regions, detailed studies of their characteristics are scarcely published in languages other than Portuguese and Spanish. To improve knowledge on Ferralsols, the International Soil Reference and Information Centre (ISRIC) has made field descriptions and sampled a considerable number of profiles of this soil class and related soils and analyzed their most important physical, chemical and mineralogical properties.

The purpose of this paper is to present the data obtained; to analyze their consistence and, or, variability; to search for possible characteristics which better describe and differentiate Ferralsols and related soils, such as Cambisols, Acrisols, Lixisols and Nitisols with low activity clays, and Alisols.

MATERIALS AND METHODS

Fifty eight soil profiles, representing Ferralsols (40) and low-activity clay Cambisols (4), Lixisols (1), Acrisols (6), Nitisols (5) and Alisols (2) of the International Soil Reference and Information Centre (ISRIC) collection, described and sampled in eighteen different countries of tropical and subtropical regions were selected for the present study. A number of profiles related to Ferralsols was included to increase the variability of properties for statistical analysis and also to test the usefulness of parameters presently in use and others which may be proposed to characterize and differentiate these soils.

The selection of the sites for soil description and the actual collection was carried out both by soil scientists from ISRIC and from local institutions, acquainted with the characteristics and distribution of the soils in each country, in order to obtain a good representativeness of the sites. Guidelines of FAO (1977) were followed. Table 1 gives details of the geographical location of soil profile description as well as their classification according to the FAO WORLD SOIL MAP LEGEND (FAO/UNESCO, 1988) and Brazilian System of Soil Classification (EMBRAPA, 1999).

Soil samples of the 58 profiles were air-dried and gently crushed to pass through a 2 mm sieve. This *fine earth* was used to perform physical and chemical analyses. Methods used were described in detail by Van Reeuwijk (1993). A brief outline of the principles is given here.

Particle-size analysis. After removal of organic matter with H_2O_2, particle-size distribution was determined by pipetting the silt and clay fraction using sodium hexametaphosphate as a dispersing agent. Water-dispersible clay was also determined by the pipette method. Particle-size distribution of selected samples was also carried out including a deferration pretreatment with sodium dithionite.

Soil pH was determined using a 1:2.5 soil-water and soil and 1 mol L^{-1} KCl ratio; o*rganic matter* by the Walkley/Black wet combustion method; *CEC and exchangeable bases* by the NH_4OAc method; exchangeable bases by leaching with 1 mol L^{-1} NH_4OAc pH 7 and measurement of Ca and Mg by atomic absorption (AAS) and K and Na by flame emission spectrophotometry (FES). Cation exchange capacity (CEC_{soil}) by replacing the NH_4 of the former determination by Na using 1 mol L^{-1} NaOAc pH 7, washing the excess Na with 80% ethanol and replacing adsorbed Na by leaching with 1 mol L^{-1} NH_4OAc pH 7 and determining Na by *FES.Exchangeable acidity and aluminium* were extracted with 1 mol L^{-1} KCl, Al determined by *AAS* and exchangeable acidity by back-titration with 0.025 mol L^{-1} NaOH.

The *sum of bases* (exch. Ca + Mg + K + Na), clay *CEC (CEC$_{clay}$* = CEC_{soil} x 100/%clay), *base saturation (BS:* sum of bases 100/CEC_{soil}), *effective cation exchange capacity of the soil* (*ECEC$_{soil}$* = sum of bases + exch. Al), clay *ECEC (ECEC$_{clay}$* = $ECEC_{soil}$ 100/%clay), and *aluminium saturation (AlS:* Al-KCl 100/CEC_{soil}) were calculated.

As the CEC_{soil} consists mainly of CEC_{clay} and $CEC_{organic\ matter}$, for a correct calculation of the CEC_{clay}, the CEC_{soil} has to be corrected for the organic matter. This was done by the procedure proposed by Bennema (1966), Bennema & Camargo (1979), and Klamt & Sombroek (1988).

Bulk density, moisture retention and *specific surface area* were determined only on samples of the A, AB or BA and B horizons of twenty five soil profiles distributed as follows: *Ferralsols:* Brazil (8), Colombia (1), Ivory Coast (1), Kenya (4), Gabon (2), Indonesia (1), Malaysia (2), Mozambique (1) and Zambia (2); *Nitisols:* Brazil (1) and Malaysia (1); and *Cambisols:* Indonesia (1).

Specific surface area was determined by the ethylene glycol monoethyl ether (*EGME*) retention method (Heilman et al., 1965).

Statistical treatment of the data sets was performed using the SPSS Statistical Package (Nie, 1975). Data of two subhorizons of the B horizon were used in soils of very deep solum (> 200 cm).

Table 1. Geographical location and classification according to FAO/UNESCO (1988) and EMBRAPA (1999) of soil profiles used in this study

Profile Code	Location	Coordinates		Classification	
		Latitude	Longitude	FAO, 1988	EMBRAPA, 1999
BR 3	Brazil, RJ, Itaperuna-Raposo	S 21º 08'	W 42º 05'	Rhodic Ferralsol	LVA[1] Dystrophic
BR 4	Brazil, SP, Bom Fim Paulista	S 21º 14'	W 47º 47'	Rhodic Ferralsol	LV Eutroferric
BR 5	Brazil, SP, Gravinhos	S 21º 21'	W 47º 44'	Geric Ferralsol	LV Acriferric
BR 6	Brazil, SP, Marilia/Assis	S 22º 33'	W 50º 19'	Rhodic Ferralsol	LV Dystrophic
BR 7	Brazil, PR, Londrina/Ponta Grossa	S 23º 40'	W 51º 10'	Rhodic Nitisol	NV Eutroferric
BR 8	Brazil, PR, Ivaipora/Pitanga	S 24º 18'	W 51º 43'	Humic Ferralsol	LV Dystroferric
BR 9	Brazil, PR, Pitanga/Guarapuava	S 25º 06'	W 51º 32'	Humic Ferralsol	LB Dystrophic
BR 10	Brazil, PR, Curitiba/Joinville	S 25º 40'	W 49º 11'	Humic Ferralsol	LVA Dystrophic
BR 11	Brazil, PA, Castanhal	S 01º 22'	W 47º 11'	Xanthic Ferralsol	LA Dystrophic
BR 13	Brazil, PA, Santarem/Cuiaba	S 02º 54'	W 54º 56'	Xanthic Ferralsol	LA Dystrophic
BR 14	Brazil, DF, Planaltina	S 15º 30'	W 47º 40'	Rhodic Ferralsol	LV Dystrophic
BR 15	Brazil, DF, Planaltina	S 15º 35'	W 47º 40'	Geric Ferralsol	LA Acric
BR S1	Brazil, RJ, Resende	S 22º 28'	W 44º 31'	Xanthic Ferralsol	LA Dystrophic
BR S2	Brazil, RS, Girua	S 28º 05'	W 54º 25'	Rhodic Ferralsol	LV Dystrophic
CM 1	Cameroon, Barombi-Kang Exp. Sta.	-	-	Haplic Nitisol	NX Dystrophic
CN 4	China, Changsha, Hunan	N 28º 12'	E 113º 05'	Haplic Nitisol	NV Dystrophic
CN 7	China, Guangzhow, Logang	N 23º 13'	E 113º 28'	Haplic Acrisol	PV Dystrophic
CO 2	Colombia, Gaitan/Porto Lopes	N 04º 10'	W 72º 55'	Ferralic Cambisol	CX Tb Dystrophic
CO 15	Colombia, San Jose del Guaviare	N 02º 30'	W 72º 38'	Plinthic Acrisol	PVA Aluminic
CO 18	Colombia, El Granha	N 02º 25'	W 72º 40'	Haplic Ferralsol	LVA Dystrophic
GA 1	Gabon, Makokou, Layon	N 00º 31'	E 12º 48'	Xanthic Ferralsol	LA Dystrophic
GA 4	Gabon, Poungan/Lebamba	S 02º 13'	E 11º 33'	Xanthic Ferralsol	LA Dystrophic
GA 5	Gabon, Ndende bridge	S 02º 21'	E 11º 23'	Xanthic Ferralsol	LA Dystrophic
IN 9	India, Hoskote/Devanahalli, Bangalore	N 13º 08'	E 77º 50'	Ferric Lixisol	PVA Eutrophic
ID 1	Indonesia, Parung, Java	S 06º 23'	E 106º 32'	Haplic Ferralsol	LVA Eutrophic
ID 2	Indonesia, Ranoamaya, Java	S 06º 39'	E 106º 49'	Humic Cambisol	CH Dystrophic
ID 15	Indonesia, Central Kalimantan	S 00º 32'	E 112º 36'	Xanthic Ferralsol	LA Dystrophic
CI 1	Ivory Coast, Tai Forest	N 05º 53'	W 07º 20'	Ferric Acrisol	PV Dystrophic
CI 4	Ivori Coast, Tai Forest	N 05º 53'	W 07º 20'	Xanthic Ferralsol	LA Dystrophic
JM 3	Jamaica, Manchester	N 18º 04'	W 77º 27'	Geric Ferralsol	LV Acric
KE 6	Kenya, Embu district	S 00º 32'	E 37º 28'	Rhodic Ferralsol	LV Eutrophic
KE 7	Kenya, Embu district	S 00º 32'	E 37º 28'	Ferralic Cambisol	CH Dystrophic
KE 11	Kenya, Sokoko, Kilifi district	S 03º 27'	E 39º 50'	Rhodic Ferralsol	LV Eutrophic
KE 29	Kenya, Cambini, Kilifi district	S 03º 37'	E 39º 50'	Rhodic Ferralsol	LV Dystrophic
MY 1	Malaysia, Serdang	N 05º 16'	E 100º 34'	Haplic Ferralsol	LVA Dystrophic
MY 3	Malaysia, Kuantan, Pahang	N 03º 40'	E 103º 30'	Geric Ferralsol	LA Acriferric
MY 5	Malaysia, Temerloh/Kuantan, Pahang	N 03º 20'	E 102º 30'	Rhodic Ferralsol	LV Dystrophic
MY 6	Malaysia, Puchong, Selangor	N 03º 02'	E 101º 37'	Ferric Acrisol	PA Dystrophic
MY 7	Malaysia, Kuala Pilah/Tampin	N 02º 44'	E 102º 15'	Geric Ferralsol	LVA Acric
MY 56	Malaysia, Kuching, Sarawak	N 01º 32'	E 110º 20'	Geric Ferralsol	LV Acriferric
MY 57	Malaysia, Lundu Sekambal, Sarawak	N 01º 40'	E 109º 52'	Xanthic Ferralsol	LA Dystrophic
MZ 2	Mozambique, Niassa, Lichinga	S 13º 08'	E 35º 16'	Rhodic Ferralsol	LV Acric
MZ 3	Mozambique, Niassa, Sanga, Unango	S 12º 57'	E 35º 23'	Rhodic Nitisol	NV Dystrophic
PE 1	Peru, Yurimaguas	S 05º 45'	W 76º 05'	Ferric Acrisol	PVA Aluminic
WS 1	Savai'i Island, West Samoa	S 13º 27'	W 172º 22'	Geric Ferralsol	LA Acriferric
SU 254	CIS, Chakva, Georgia (GLINKA MEMORIAL COLLECTION)	N 41º 45'	E 41º 45'	Humic Alisol	-
SU 256	CIS, Makahradze, Georgia (GLINKA MEMORIAL COLLECTION)	N 41º 55'	E 42º 02'	Ferric Alisol	-
ZA 2	South Africa, Hermansburg, Natal	S 29º 04'	E 30º 47'	Rhodic Ferralsol	LVA Acric
ZA 20	South Africa, Highover, Richmond	S 29º 55'	E 30º 04'	Ferralic Cambisol	CH Dystrophic
US 3	United States, Lexington, North Carolina	N 35º 50'	W 80º 27'	Rhodic Nitisol	NV Eutrophic
US 8	United States, Dahu Isl., Kunia, Hawaii	N 21º 24'	W 158º 02'	Rhodic Ferralsol	LV Eutroferric
US 9	United States, Dahu Isl., Waipio, Hawaii	N 21º 26'	W 158º 00'	Rhodic Ferralsol	LV Eutroferric
US 10	United States, Kauai Isl., Wailua, Hawaii	N 22º 04'	W 159º 24'	Geric Ferralsol	LVA Acric
ZM 2	Zambia, Kasama District, N. Prov.	S 10º 13'	E 31º 08'	Rhodic Ferralsol	LV Dystrophic
ZM 4	Zambia, Mbala/Kasama, N. Prov.	S 08º 50'	E 31º 24'	Rhodic Ferralsol	LV Dystrophic
ZM 5	Zambia, Kasama District, N. Prov.	S 10º 13'	E 31º 08'	Xanthic Ferralsol	LA Dystrophic
ZM 8	Zambia, Kasama District, N. Prov.	S 10º 10'	E 31º 08'	Ferric Acrisol	PVA Dystrophic
ZM 9	Zambia, Kasama District, N. Prov.	S 10º 10'	E 31º 11'	Xanthic Ferralsol	LA Dystrophic

[1] LA = Yellow Latosol; LB = Brown Latosol; LVA = Red Yellow Latosol; LV = Red Latosol; PA = Yellow Argisol; PVA = Red Yellow Argisol; PV = Red Argisol; CX = Haplic Cambisol; CH = Humic Cambisol; NX = Haplic Nitosol; NV = Red Nitosol.

RESULTS AND DISCUSSION

Environmental conditions of sampling sites

Ferralsols and related soils are found in tropical and subtropical humid and sub-humid regions. The occurrence of these soils in semi-arid and arid climates suggests that they represent relics of former wetter climates (SCS/USDA, 1975; Lepsch et al., 1982; Lücken et al., 1982). According to the concepts defined in Soil Taxonomy (SCS/USDA, 1975), most of the profiles occur in regions with udic (50%) and ustic (43%) soil moisture regimes. Only 5% of them occur under perudic and only 2% under torric conditions. The predominant soil temperature regimes are isohyperthermic (45%) and thermic (34%); while 17% is hyperthermic and 2% isothermic and isomesic, respectively.

These soils occur mainly on old and stable landscapes (SCS/USDA, 1975). As for the regional type of physiography, more than half of the profiles were sampled on broad gently undulating to undulating plateaus, 15% on broad hills with depressions, 12% on erosional plains, 5% on alluvial terraces and 4% respectively on low hills and gently sloping fluvio-lacustrine terraces, one profile coming from a karst depression (ISRIC, 1985). In terms of slope gradients, 30 profiles were sampled on flat surfaces (< 2% slope), 20 profiles on gently sloping to sloping surfaces (2-8%), five profiles on strongly sloping (8-16%), and one profile on moderately steep (16-30%) and one on steep sloping (30-55%) surface, respectively.

The parent material from which Ferralsols and related soils have developed is presented at table 2. Weathering commonly has proceeded to great depths and produced a thick regolith. Erosional and depositional processes have reworked the parent material in many tropical and subtropical environments (Schwertmann et al., 1983). Most of these materials, and soils derived from them, were subjected to several cycles of climatic and thus biological changes (Bigarella, 1964). So, the soils originating in these conditions show a great variety of characteristics, due to variation in the original parent material and subsequent forms of alteration they have undergone.

A listing of the original vegetation found on the sampling sites is given on table 3. The natural vegetation on two thirds of the sites has been substituted by cultivated crops or grassland.

Well drained soils occur on 85% of the description sites; 12% are somewhat poorly drained and 3% somewhat excessively drained. Erosion, when indicated, is predominantly slight sheet erosion, but on 15% of the sites, moderate sheet and, or, gully erosion have been reported.

Morphological characteristics of the soils

The morphological features common to most Ferralsols are very deep solum (> 200 cm), diffuse boundaries between horizons and good internal drainage in contrast to the somewhat shallower sola with clear to gradual horizonation of Cambisols, Acrisols, Lixisols, Nitisols and Alisols.

Colour is the most prominent morphological feature of these soils, with hues varying from 10R to 10YR, values from 3 to 7 and chromas from 2 to 8.

Table 2. Distribution of the profiles according to parent material

Parent material	Percentage of profiles	Number of profiles
Sedimentary: sandstone, limestone, unspecified	14	8
Volcanic:		
a) Ejecta ash (andesitic) and tuff	7	4
b) Coarse-grained, intermediate and acidic (diorite, granodiorite, granite)	11	7
c) Fine-grained, intermediate and basic (diabase, basalt, andesite, spillite, dolerite, phonolite)	25	14
Metamorphic:		
a) Acidic (migmatite, gneiss, schist)	9	5
b) Basic (charnokites, serpentinites, calcaric schist)	5	3
Unconsolidated material:		
a) Sandy clay texture	11	7
b) Clayey texture	14	8
Unknown	4	2

Table 3. Type of original vegetation on the soil sites

Type of vegetation	Percentage of profiles	Number of profiles
Evergreen to semi-deciduous closed forest	44	25
Evergreen to semi-deciduous open woodland	16	10
Evergreen to semi-deciduous shrubs	14	8
Herbaceous vegetation	14	8
Unknown	12	7

Table 4. Clusters of Ferralsols and related soils based on their colour hues, values and chromas

Number of cluster		Number of samples	Hue	Colour values	Chroma	Soil colour
I	1	16	10R - 1.5YR	3	3 - 4	Dusky red
	2	28	1YR - 2.5YR	3 - 5	4 - 8	Dark red to red
II	3	5	5YR	3 - 4.5	3 - 4	Dark reddish brown to reddish brown
	4	16	5YR - 6YR	3.5 - 5	5 - 8	Yellowish red to reddish yellow
III	5	13	6.5YR- 7.5YR	4 - 7	6 - 8	Strong brown to reddish yellow
	6	19	9YR - 10YR	3.5 - 6	6 - 8	Dark yellowish brown to yellow
IV	7	5	7.5YR- 10YR	3 - 4	2 - 4	Dark grayish brown to dark brown

Clustering these soils on the basis of hues, values and chromas of the diagnostic subsurface horizons yielded seven clusters (1 to 7, Table 4) of soils with different colours. This number can be reduced to four (I to IV) by considering the narrow range of hues of clusters 1 and 2, 3 and 4, and 5 and 6.

Cluster I is formed by soils with Rhodic properties (FAO/UNESCO, 1988), with the exception of some profiles with too high values and, or, chromas; cluster II by those with Haplic properties; cluster III with Xanthic properties, with the exception of one profile with too low colour values; and cluster IV, comprising dark grayish brown to dark brown soils, which do not fit in the other soil units based on soil colour. Their low colour values and chromas are related to a high organic matter content, which in turn is related to specific environmental conditions, since these soils are found in udic and perudic soil moisture regimes (SCS/USDA, 1975). Studies of Kämpf & Schwertmann (1983), Torrent et al. (1983), Curi & Franzmeier (1984), Kämpf & Klamt (1984), and Schwertmann (1985) have shown that red and yellow hues are related to the proportion of hematite and goethite in the soil material.

Kämpf & Klamt (1984) proposed to divide Brazilian Latosols into three units based on Hm/(Hm + Gt) ratios and soil colour:

(1) mainly goethitic soils, with $Hm/(Hm + Gt) < 0.2$ and hues yellower than 6YR;

(2) goethitic-hematitic soils, with $Hm/(Hm + Gt) = 0.2\text{-}0.6$ and hues between 6YR and 3YR; and

(3) mainly hematic soil, with $Hm/(Hm + Gt) > 0.6$ and hues 2.5YR or redder.

There is a good relationship between these three units and the clusters obtained since cluster I fits into unit (3); cluster II into unit (2) and clusters III and IV into unit (1). Colour as used in the FAO (1988) Revised Legend of the Soil Map of the World is consistent with these data, but it is proposed that the hues of Rhodic Ferralsols should be set at 3YR or redder and of the Xanthic units at 6YR or yellower.

Mottles were described in a few profiles, occurring as lithorelics (BR 7, BR 10 and US 10) or related to iron segregation (CN 4) and iron concretions and stones (GA 5, CI 4 and CO 15). This is ascribed to the fact that, with the exception of the Plinthic unit, Ferralsols are well drained soils.

The presence of clay skins (argillans) is a morphological feature not expected to occur in Ferralsols. However, three profiles, classified as such, show patchy clay skins while four have broken thin clay skins. All the Nitisols show continuous, moderately thick to thick argillans; most Acrisols broken thin to moderately thick, and one of the three Cambisols broken thin clay skins. The presence of clay skins, next to other properties, is a diagnostic feature used to separate soils with Argic from soils with ferralic B horizons, and thus Ferralsols from Nitisols and Acrisols. According to Moormann & Buol (1981), the classification of soils with low-activity clay, having a textural gradient fulfilling the requirements for Argic B horizons, but with the absence of clay skins, is one of the most severe problems. The present study, however, indicates that clay skins seem to constitute a consistent accessory characteristic to differentiate soils with an Argic or Nitic horizon from a Ferralic B horizon.

The Ferralsols predominantly have a weak, very fine, medium and coarse subangular blocky and porous massive structure, while in the other soil groups the structure is moderate to strong, fine to coarse, angular and subangular blocky. According to Sanchez (1976) many Oxisols in constantly humid climates (udic and perudic) belong to the Tropeptic subgroup (SCS, 1975), because the structure tends toward the blocky type. From the five profiles classified in the Tropeptic subgroup, two occur in udic/isohyperthermic (ID.15 and MY.56) and three in ustic thermic (MZ.2) and isothermic (ZM.09) and isohyperthermic (US.09) environments.

Very strong, very fine to fine, granular or crumb structure, referred to as “coffee powder”- like structure, has its maximum development in subsurface horizons of a gibbsitic-hematitic clayey Ferralsol (BR 5), decreasing in degree of development toward gibbsitic/kaolinitic-hematitic (KE 6 and 11 and MZ 2) and kaolinitic-hematitic (BR 8) soils.. Nitisols with this type of structure in the lower part of the B horizon (BR 7) - which indicates the presence of a Ferralic diagnostic horizon below an Argic - are classified as Latosolic Structured Red Earths (*Terra Roxa Estruturada Latossólica*) in the soil classification used in the Brazilian soil surveys (Camargo et al, 1987). Very strong, very small aggregates occur also in the gibbsitic-goethitic soils (JM 3, WS 1, US 10), but their macrostructure has been described as weak to moderate, fine to large, subangular and angular blocky and massive porous. The structure of most yellow red to red, predominantly kaolinitic-goethitic Ferralsols is weak to moderate, fine to coarse, subangular blocky. The stronger development of structure at the surface horizons is probably related to the effect of organic matter on structure.

The strong, very fine to fine, granular or crumb structure (coffee powder) has been attributed to the influence of biological activity (mainly termites; Verheye & Stoops, 1975). The influence of sesquioxides (Al and, or, Fe oxides/hydroxides, mainly gibbsite and hematite) on the aggregation of primary particles has been described by Baver et al. (1973) and is also evident from the present study. Lima (1984) identified gibbsitic grains in Brazilian Latosols (Humic Ferralsol). The combined effect of biological activity and mineralogical composition on the formation and preservation of this type of soil structure deserves to be further investigated.

In spite of the clayey texture, most Ferralsols have a slightly hard, very friable to friable, slightly sticky to sticky and slightly plastic to plastic consistence. Kaolinite and sesquioxides are responsible for these properties. The other soil groups have a hard, very friable to firm, slightly sticky to very sticky and slightly plastic to very plastic consistence. Yellow and clayey kaolinitic Ferralsols (BR 13 and BR S1), in natural conditions, have a somewhat dense layer in the upper part of the B horizon. These soils have been termed cohesive Yellow Latosols (EMBRAPA, 1996) and present at the upper part of the B horizon, hard to very hard consistence when dry and friable when moist, as well as disorganized structure, high density, low porosity and enrichment by silica, aluminium and iron oxihydroxides. These properties have been ascribed to processes of illuviation of clay and organic compounds and, or, clay destruction (EMBRAPA, 1996).

Most of the soils have many, very fine to medium, tubular and interstitial pores, which renders them very porous. Roots are many, fine to medium, in the surface horizon, decreasing in quantity and size with depth. Pedofeatures such as clay balls and pedotubules are common in these soils, as well as the reworking of soil material by termites, ants, worms, etc.

Spherical iron and, or, manganese concretions are found in one out of five of the Ferralsols under investigation and are few to frequent and small to medium and hard. They may also occur in Nitisols and Acrisols. Rock and primary mineral fragments do not frequently occur in these deeply weathered soils, but were described in some profiles (BR 7, US 10).

Particle Size Distribution

In frequency distribution diagrams, the sand and silt fractions of all soils show an asymmetrical, positively skewed and leptokurtic frequency distribution. The clay fraction of all soils shows an almost normal distribution, whereas that of the Ferralsols is skewed. In all cases, a tendency to bimodal distribution can be discerned. A concentration of samples on the sand-clay side of the textural triangle is obtained when the data of only the diagnostic subsurface horizon of Ferralsols are plotted (Figure 1b), if compared to the plot of all samples (Figure 1a).

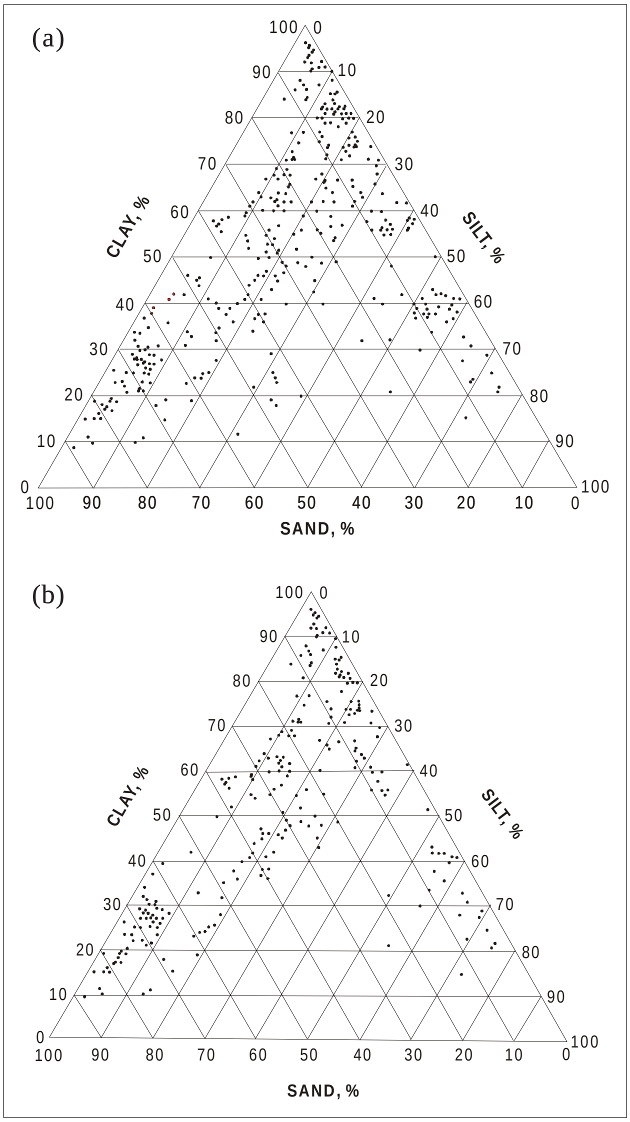

Figure 1. Plots of the soils by their texture (particle size distribution): (a) all samples, (b) samples of A and B horizons of Ferralsols.

More than half of the soils (56%) have a clayey texture, followed by sandy clay loam (18%), sandy clay (15%), clay loam (5%), and silty clay types (5%) while one profile consists of sandy loam and one of silt loam. Clay increase and textural change with depth is by definition negligible in typical Ferralsols (BR 5 and ID 15) and Cambisols (ID 2), but slight in intergrades between Ferralsols and Nitisols (MZ 2) and gradual/clear in typical Acrisols (ZM 8) and Nitisols (BR 7) (Figure 2). Three profiles are very gravelly, the gravel consisting mainly of iron concretions. One Ferralsol (CI 4) and one Acrisol (CI 1) have ironstone (petroferric layer) in the lower part of the B horizon.

A low silt content is a common characteristic of these deeply weathered soils, because primary minerals are unstable in this fraction and secondary minerals are found mainly in the clay fraction. The silt/clay ratio has been used as weathering index and soil classification parameter. Soils with a silt/clay ratio of 0.15 are regarded as highly weathered (Young, 1976), a ratio < 0.7 is one of the requirements used to differentiate soils having a Latosolic B horizon from soils with a Incipient (Cambic) B horizon, in the soil classification used in Brazilian soil surveys (Camargo et al., 1987), and < 0.2 in the Ferralic B horizon of the revised legend of the FAO/UNESCO Soil map of the World (FAO, 1988).

The high silt content found in some oxidic profiles (JM 3, WS 1, US 8, US 10) is related to strong aggregation of particles and to the failure of properly dispersing them by the method used. Microscopic inspection showed that the silt fraction indeed consisted of pseudo-silt or spseudomorphic gibbsitic grains as described by Lima (1984). Special

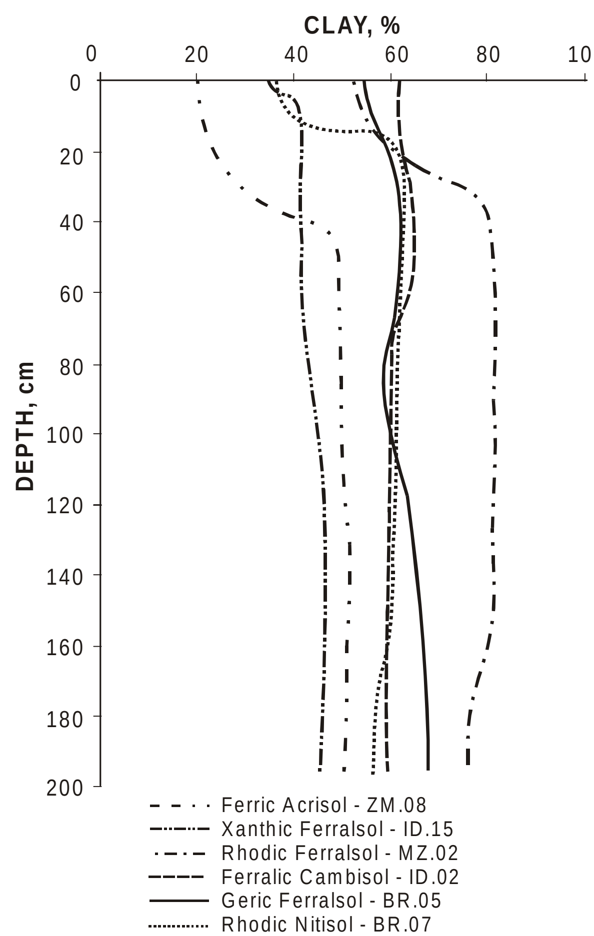

Figure 2. Clay distribution in profiles of representative upland soil of humid and subhumid tropical regions.

dispersing agents and conditions (Uehara, 1979) or deferration is required to achieve adequate dispersion. This is illustrated in table 5, which gives the particle-size distribution of profile JM 3 obtained with and without deferration pretreatment. Deferration substantially increased the clay yield in all horizons.

Most soils have a low sand content. However, soils developed from sandstone (BR 6, KE 11 and 29, MY 6, ZM 2 and 5), coarse acidic igneous rocks (MY 57) and unconsolidated sandy clay sediments (BR 11, ZM 9) have high contents of sand and thus caused the bimodality of the sand content distribution curve when all soils are considered.

Cluster analysis applied to sand, silt and clay data or only to sand and silt data of the diagnostic B horizons of Ferralsols, yielded five well defined clusters, as schematically represented in table 6. Cluster 1 with 66% sand and 28% clay fits into the fine loamy particle-size class established for differentiation at family level in Soil Taxonomy (SCS/USDA 1997) and into the medium textured class of FAO (1988); cluster 2 is fine silty and medium textured, respectively. Clusters 3 and 4 fit into fine textured class of FAO (1988) and clayey of Soil Taxonomy (SCS/USDA, 1997); cluster 5 into fine and very fine clayey textured class, respectively.

All soils developed from sandstone, unconsolidated sandy clay materials and coarse acidic and intermediate igneous rocks fall into the fine loamy cluster 1. The fine silty cluster 2 is composed of samples with strong aggregates, which were not properly dispersed (pseudo-silt) but which disappeared with the use of stronger dispersing agents and, or, by deferration of the samples. The silty clay (no. 3), sandy clay (no. 4) and clayey (no. 5) clusters are made up of samples belonging to soils weathered from volcanic extrusive, fine intermediate and basic igneous rocks as well as from clayey sediments. This relation of parent material to texture of the soils is expected since all of these soils have undergone very intensive weathering and primary minerals should have been totally altered to secondary minerals. Quartz seems to be very stable, even in tropical and subtropical environments, and is held responsible for the coarser textures.

Table 5. Particle-size analysis of profile JM 3 with and without deferration

Horizon	Depth	Non-deferrated			Deferrated		
		Sand > 50	Silt 50-2	Clay < 2 µm	Sand > 50	Silt 50-2	Clay < 2 µm
	cm	%					
Aps1	0-10	4	49	47	4	28	68
Aps2	10-27	4	50	46	5	19	76
Bs1	27-88	3	53	44	2	11	87
Bs2	88-153	1	49	50	1	32	67
Bs3	153-180	1	59	40	1	30	69

Table 6. Clusters of textural classes obtained by clustering sand, silt and clay fractions of Ferralsols diagnostic B horizons

No. of cluster		No. of samples	Particle-size fraction(1)					Particle-size classes(2)
			Sand		Total sand	Silt	Clay	
			Coarse	Fine				
			wt%					
1	1	29	28.6 (0-51)	37.0 (15-55)	65.6 (49-75)	6.7 (1-23)	27.9 (20-38)	Fine loamy
2	2	17	3.7 (0-13)	3.5 (1-11)	7.2 (1-24)	61.4 (51-57)	31.4 (51-42)	Fine silty
3	3	10	2.6 (0-8)	4.8 (0-9)	7.4 (0-17)	37.3 (32-43)	54.9 (41-62)	Clayey
	4	26	10.8 (1-27)	18.9 (8-28)	29.7 (20-41)	16.8 (5-28)	53.2 (36-68)	
4	5	42	2.5 (0-6)	3.9 (0-11)	6.4 (1-16)	14.0 (2-25)	79.2 (60-96)	Very fine clayey

(1) Mean values and range. (2) According to SCS/USDA (1997).

Specific Surface Área

As in the case of particle-size distribution, the frequency distribution of specific surface area is also asymmetrical, positively skewed but mesokurtic, underscoring a relationship between these two parameters. The absolute values (Table 7) range from 14 (BR 6) to 165 $m^2 g^{-1}$ of soil (ID 2), the former having a low (20%) and the latter a high clay content (82%).

Specific surface area is closely related to particle-size and soil parent material, but does not seem to be related to soil groups as presently defined in FAO/Unesco and Soil Taxonomy. Soils with a sandy texture, weathered from sandstone, sandy clay sediments and coarse intermediate and acidic igneous rocks, show low values of specific surface area (< 50 $m^2 g^{-1}$), with the exception of profiles MZ 3 and ZM 4 developed from diorite, with values of 70 and 75 $m^2 g^{-1}$, respectively. Soils with silty clay and sandy clay texture, developed from clayey sediments (55 to 62 $m^2 g^{-1}$ with exception of BR 10) and metamorphic rocks (65-95 $m^2 g^{-1}$) show intermediate values. Clayey soils weathered from extrusive volcanic material (ID 1 and 2: 145 $m^2 g^{-1}$) and fine basic igneous rocks (BR 7, BR 9, BR-S 2, MY 3 and US 9: 105-135 $m^2 g^{-1}$) and from Georgia (SU) (135-145 $m^2 g^{-1}$) with unknown parent material, have high values of specific surface. The Indonesian soils contain halloysite and metahalloysite and traces of allophane as main clay minerals; the Brazilian soils with large specific surface area contain hydroxi-Al interlayered vermiculite and probably poorly ordered kaolinite; whereas the Russian profiles have mixed layer clay minerals, which may explain the high values obtained for specific surface area. Soils weathered from fine basic igneous rocks and clayey sediments with very strong fine aggregates, such as BR 5 and JM 3, have specific surface areas of 60 and 62 $m^2 g^{-1}$, respectively, which is low considering their clayey texture. Apparently, aggregation causes clay particles to be shielded off to some extent.

Soil pH

Soil pH shows a normal distribution (Figure 3a) while the data of other chemical properties show asymmetric, positively skewed and leptokurtic frequency distributions, regardless of data of all samples (Figure 3b), or only if B horizons or ferralic B horizons are considered (Figure 3c), which is consistent with the concept of these deeply weathered soils, with low base saturation and CEC.

Most of the soils are acid. Although the values range from 3.5-7.0, more than 80% of the samples analysed have pH values below 5.7. The Rhodic Nitisol (BR 7 and US 3), eutrophic Rhodic Ferralsols (BR 4, KE 6, US 9) and one Geric Ferralsol (MY 7) have pH values above 6. With the exception of subsurface horizons of eight Ferralsols, the pH in water is higher than in 1 mol L^{-1} KCl (negative ΔpH), indicating that most soils under study have a net negative charge (Raij & Peech, 1972; Keng & Uehara, 1974; Sanchez, 1976; Uehara, 1979; Uehara & Gillman, 1980; Bowden et al., 1980). The Ferralsols with a positive ΔpH have a dominantly sesquioxidic mineralogy (BR 15, MZ 2, MY 56, WS 1, ZA 2, US 10). Naturally, a range in mixed composition can be found, in some cases yielding a (nearly) zero ΔpH, e.g. KE 6, Bw Horizon.

Exchangeable bases

Because of the intense leaching, the content of exchangeable bases is generally very low in the soils studied (Table 8). Higher values occur in eutrophic Rhodic Nitisol and Rhodic Ferralsols, and the lowest in Xanthic, Geric and Humic Ferralsols and Ferric Acrisols. The mean base saturation is 24% (± 23) for all samples and 22% (± 24) for ferralic horizons (Figure 3d).

Exchangeable Al

As expected, values of exchangeable aluminium are very low in Rhodic Nitisols and Geric Ferralsols and higher but variable in the other soil units (Table 8). The values for exchangeable Al (and Al saturation) in the ferralic B horizons generally increase in the following order: Geric < Humic < Haplic < Rhodic < Xanthic Ferralsol. In some Ferralsols, exchangeable Al (and Al saturation) decreases with depth (BR 3, 8, 9; MY 1, 5) and, in

Table 7. Frequency distribution of specific surface area

Sample	Specific surface area					Standard deviation	Variance	Standard error	Skewness	Kurtosis
	Min.	Max.	Mean	Mode	Median					
	$m^2 g^{-1}$									
All B horizons	14.0	165	75	60	72	36.5	1335	3.8	0.5	-0.3
Ferralic B hor.	14.0	153	73	54	72	34.3	1180	4.2	0.3	-0.3

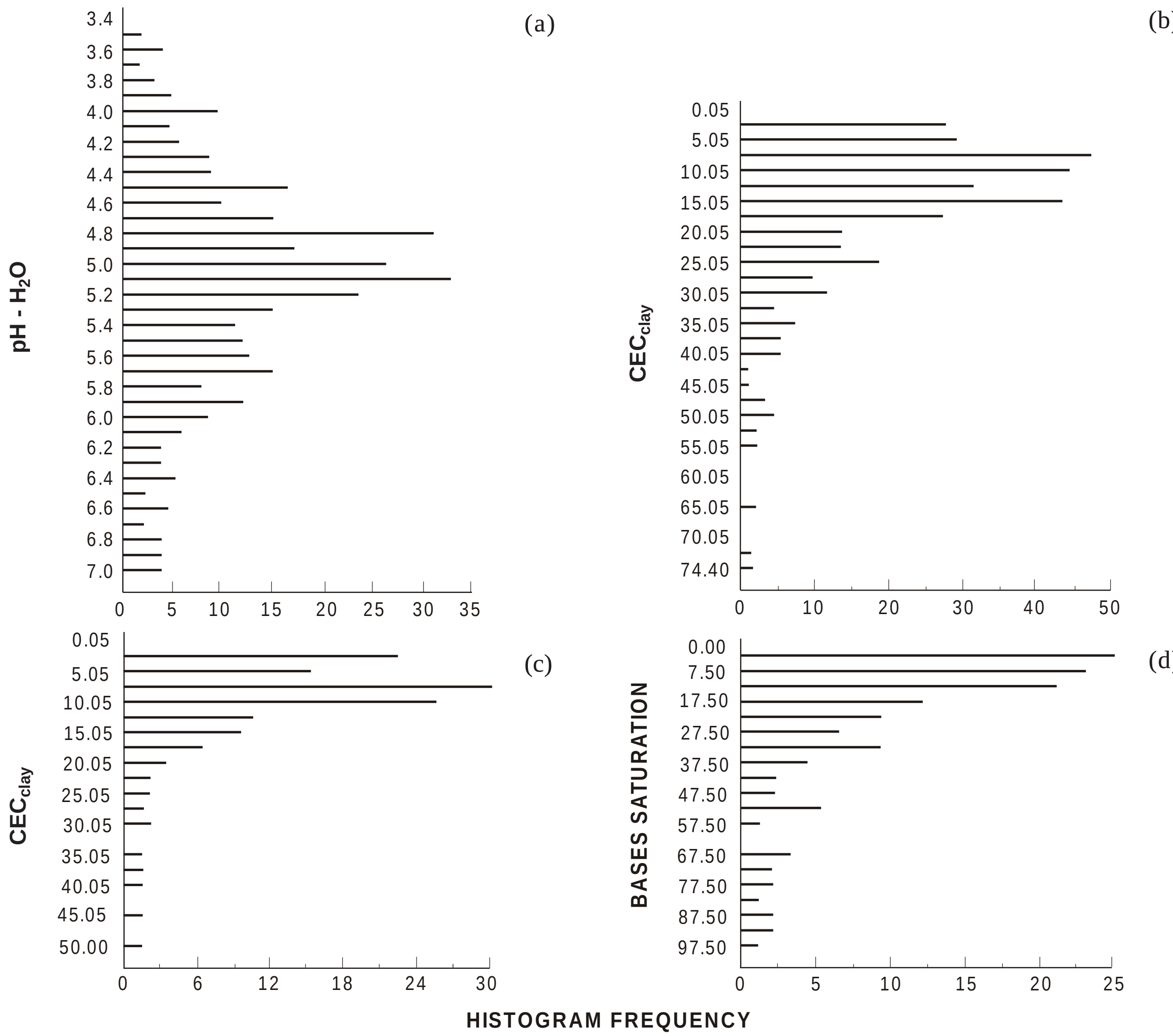

Figure 3. Frequence distribution histogram of pH (a) and CEC_{clay} (b) for all samples analysed and CEC_{clay} (c) and base saturation (d) of soils with Ferralic B horizons.

Table 8. Mean values of exchangeable bases and CEC_{soil}

	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Sum	Al^{3+}	CEC_{soil}	Base saturation
	cmol$_c$ kg^{-1}							%
All samples	1.2	0.5	0.5	0.1	2.3	1.2	6.7	24
Ferralic B	0.7	0.4	< 0.1	0.1	1.3	0.7	4.9	22

others, increase with depth (BR 6, 11, 13, S 1; CO 15; GA 4; ZM 2, 5). This distribution is an important characteristic to consider for soil management purposes, since exchangeable Al behaves as an inhibitor for plant root development (Ritchey et al., 1980).

Cation Exchange Capacity

The soils under study have a low cation exchange capacity (Table 8), which is related to the mineralogy of the clay fraction, consisting mainly of kaolinite and oxihydroxides of Fe and Al with low variable surface charge (Zelagny & Calhoun, 1971; Uehara, 1979; Bowden et al., 1980). The values are lower in ferralic B horizons (CEC = 4.9 ± 8.5 $cmol_c\ kg^{-1}$) as compared to non-ferralic B horizons (6.7 ± 5.3 $cmol_c\ kg^{-1}$). Except in four non-Ferralsols, the CEC decreases substantially from the surface to the subsurface horizons, indicating a strong influence of organic matter on the exchange properties. Higher values for non-ferralic B horizons are related to the presence of 2:1 and 2:1:1 clay minerals with more expressive permanent negative charge contribution in these soils.

Organic carbon

The mean content of organic carbon in the surface horizons of the Ferralsols of this study is 2.73% (range: 0.6-10.2%). In the B horizons, this value is significantly lower: 0.48% (0.07-1.37%). Humic and Geric units have higher contents than Haplic, Xanthic and Rhodic units.

The graphical procedure proposed by Bennema (1966) and Bennema & Camargo (1979) to estimate the contribution of organic carbon to the CEC of soil applied to the sample BR 9 is indicated in figure 4. The very high correlation coefficients (r > 0.99) obtained indicate that, in these soils, the exchange properties are related mainly to organic matter and clay content. The same procedure applied to Nitisols, Acrisols and Cambisols, yielded lower correlation coefficients, suggesting that the contribution of organic carbon and clay is not uniform throughout the profile (clay increase with depth and possible changes in clay mineralogy and, or, composition of organic matter is responsible for these differences).

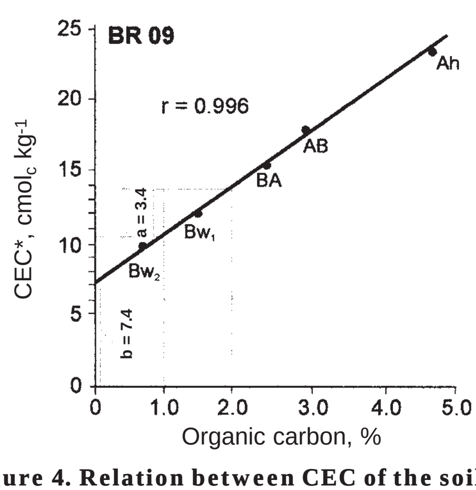

Figure 4. Relation between CEC of the soils and its contributors clay and organic carbon of profile BR 09 (based on procedures of Bennema, 1966 and Bennema & Camargo, 1979). * Units of both abcissa and ordinate were converted to 100% clay basis, e.g., for each horizon direct results of % C and CEC soil multiplied by 100/% clay.

The average contribution of each % organic matter to the CEC of the Ferralsols is 3.4 $cmol_c\ kg^{-1}$ of soil (range: 1.4 to 9.4), while the average CEC of clay is 7.0 $cmol_c\ kg^{-1}$ (range: -1.7 to 16.2), according to Klamt & Sombroek (1988). This mean value for organic matter is lower than the "correction factor" of 4.5 in the equation:

$$CEC_{clay} = \frac{CEC_{soil} - (\%C - 4.5)}{\%clay} \times 100$$

used to calculate the CEC of the clay fraction corrected for organic matter in the system of soil classification used in Brazilian soil surveys (EMBRAPA, 1981; Camargo et al., 1987). However, this value of 3.4 is about midway the range for humic acids given by Sposito (1989) and happens to equal the mean value (at pH 7) of sixty Wisconsin soils (Bohn et al., 1979).

The CEC of organic matter (expressed per % of carbon) is on the average lower in Geric (range: 1.3-3.6 $cmol_c\ kg^{-1}$) and Humic (2.0-3.6 $cmol_c\ kg^{-1}$) than in Xanthic (1.6-6.8 $cmol_c\ kg^{-1}$) and Rhodic (2.4-9.4 $cmol_c\ kg^{-1}$) Ferralsols. The proportional contribution of organic matter to the CEC_{soil} in A horizons is found to be high in all soils. This is particularly the case in Geric (53-77%), Humic (39-78%) and Haplic (36-67%) Ferralsols. As expected, in the subsurface horizons these values are lower: 18% on the average, with 12% in Xanthic, 21% in Rhodic, 22% in Geric, and 24% in Humic Ferralsols. The type of vegetation, land use and climatic zones in which Ferralsols occur do not considerably influence the values obtained.

The contribution of organic matter to the CEC of Ferralsols should be considered in determining the CEC of their clay fraction. The lack of clear trends in the contribution of organic matter to the exchange properties and the amplitude of variation obtained, suggest that this determination needs to be done for each soil profile individually, by using the procedure of Bennema (1966) and Bennema & Camargo (1979).

Regression analysis applied to CEC data resulted in low correlation coefficients between CEC_{clay} and clay content, regardless of all samples (r = 0.27); samples of all B horizons (r = 0.39), or only ferralic B horizons (r = 0.29; Figure 5a) were tested. These results reflect the difficulty to disperse some soils with the procedure used to determine particle-size distribution and the asymmetrical distribution of the data. Higher values (r = 0.61) were obtained for non-ferralic B horizons, which can be ascribed to their more permanent-charge clay mineralogy contributing to the CEC and less problematic dispersion.

A somewhat higher correlation exists between CEC_{soil} and organic carbon content for all samples (r = 0.66), but the coefficient decreases when samples of all B horizons (r = 0.32) or ferralic B horizons (r = 0.32) are considered. This points again to the significant contribution of organic matter to the CEC.

By applying stepwise multiple regression analysis, the independent variable with highest correlation to the dependent CEC_{soil}, i.e. organic carbon, was obtained with $r = 0.66$ in the first step. This was improved to r = 0.69 and $r = 0.73$ when the influence of the variables silt and silt and clay were considered in steps two and three, respectively. Square and log functions improved the correlation coefficients slightly, such as in the case of CEC_{soil} with clay content, from $r = 0.27$ to $r = 0.34$.

The correlation coefficient between CEC_{soil} of all samples and specific surface area was the highest obtained ($r = 0.72$). The r value decreased to 0.63 (Figure 5b), when data of only ferralic B horizons were analysed, and to 0.18 when correlating specific surface area with CEC_{clay}, indicating once again the unreliability of the particle-size data.

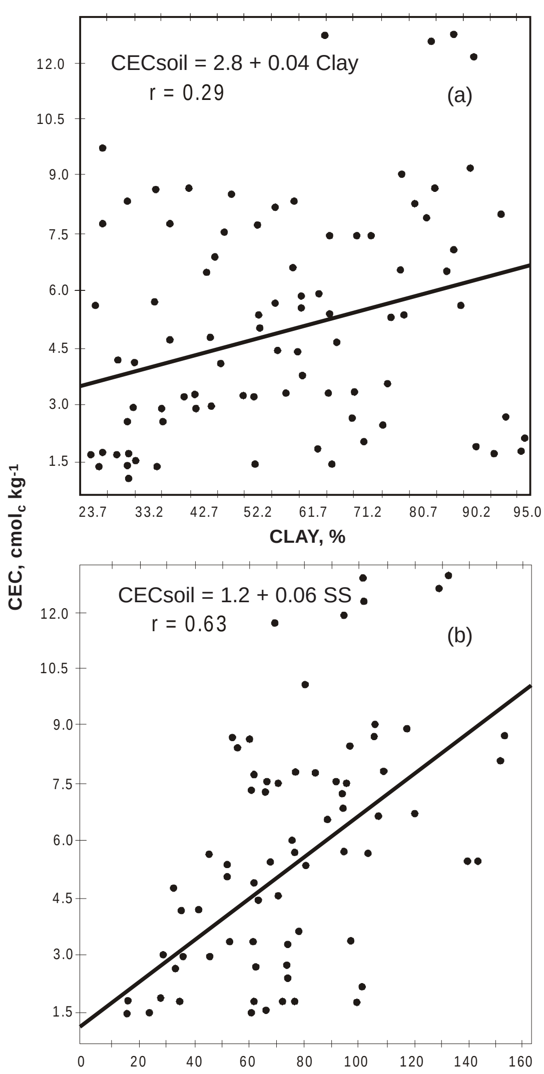

Figure 5. Correlation between: (a) CEC of Ferralic B horizons and clay content, (b) CEC of Ferralic B horizons and specific surface area.

CONCLUSIONS

1. The Ferralsols and low activity clay Cambisols, Lixisols, Acrisols and Nitisols and Alisols studied, occur mainly on old and stable landscapes of flat to gently sloping relief, udic and ustic moisture regimes, isohyperthermic and thermic temperature regimes, forest and open wood land and weathered from a great variety of types of parent material.

2. Very deep solum (> 200 cm) and diffuse boundaries between horizons are features common to Ferralsols in contrast to the somewhat shallower sola with clear to gradual horizonation of Cambisols, Lixisols, Acrisols, Nitisols and Alisols.

3. Colour is the most prominent morphological feature of the soils studied, which allowed clustering them in four distinct classes on basis of colour hues, values and chromas. The clusters represent, respectively, rhodic, haplic, xanthic and humic properties.

4. Frequence diagrams show an asymmetric, positively skewed and leptokurtic distribution for sand and silt content, specific surface, exchangeable bases and cation exchange capacity, which is consistent with the definition of Ferralsols.

5. With the exception of Rhodic Nitisols and Rhodic Ferralsols, the soils are acid with low exchangeable bases and low cation exchange capacity.

6. Regression analysis between CEC and silt and clay content rendered low correlation coefficients due to the difficulty in dispersing some of these soils for particle size analysis as well as for the asymmetric frequence distribution of these data. Correlations were higher between CEC and organic carbon and specific surface and clay content.

7. In addition to clay increase with depth, particle size classes, soil colour, cation exchange capacity, base saturation - which are characteristics already used to describe and differentiate the soils studied - soil structure, consistency and specific surface area can also be used for this purpose, particularly for distinguishing soil subunits.

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