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Indian land use in the Raposa–Serra do Sol Reserve, Roraima, Amazonia, Brazil: Physical and chemical attributes of a soil catena developed from mafic rocks under shifting cultivation

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ABSTRACT

Native Indians (Macuxi, Ingarikó and Uapishana) in the Raposa–Serra do Sol Indian Reserve have been cultivating forest soils since the early XIX century, especially those derived from dolerite sills, scattered within the quartzitic dominated landscape. Representative soils developed from mafic rocks under Indian shifting cultivation in northeastern Roraima, were submitted to physical, chemical and mineralogical analyses to characterize their pedogenetic characteristics and infer on their status under native Indian shifting cultivation. The soil profiles were classified as: Orthic Ebanic Chernosol (USDA Mollisol), vertic Orthic Ebanic Chernosol (USDA Mollisol), Eutrophic Haplic Cambisol (USDA mollic Inceptisol) and Eutrophic Red Nitosol (USDA Red Alfisol), which occupy, respectively, lower slopes and less dissected terrains (Mollisols) and steeper slopes (Alfisols). The first two are eutrophic, and not typical of the Amazon region. Their mineralogies range from kaolinite/goethite rich upland, deeply weathered Nitosol, to 2:1 clay rich downslope Chernosols. The latter has primary minerals in the silt fraction and high CEC resulting in high fertility. The Nitosols reveal a process of severe topsoil loss, due to widespread sheet erosion from deforestation and shifting cultivation. Chemical analyses showed varied soil fertility, ranging from high levels in the Chernosols to a low level in the non-cultivated Nitosol. Phosphorus levels are limited in all soils, despite the high fertility. The Chernosols located in lowland, flat areas close to the valley floor are more suitable environments for the slash-and-burn native farming system. In the Chernosols and Cambisols, the clay activity below the value limit for this class indicates a current natural process of increasing leaching. The more weathered and eroded Nitosol showed low Fe-oxalate and Si-oxalate levels. Micronutrients such as total zinc and copper, decreased with depth and weathering. The Nitosols showed the highest phosphate adsorption levels (1.574 mg g^{-1} of soil) which can be attributed to its clayey texture. Chernosols showed overall lower P adsorption values, increasing with depth. All soils under native Indian cultivation display signs of physical and chemical degradation due to shortened fallow under intense land use pressure in the Raposa–Serra do Sol Reserve.

1. Introduction

The Indian population has grown continuously in Roraima, especially in the last 40 years of increasing NGO and federal government support, accompanied by better health public services. Since the early 19th Century in the Raposa–Serra do Sol Reserve, Macuxis, Ingarikós and Uapishana Indians have been the dominant groups, occupying the soils most suited for shifting cultivation.

The Macuxi population in this reserve reached more than 16,000 people, and caused growing demand for basic food production, including maize and cassava. It now places strong pressure on soil use to meet these demands, especially in limited areas of high natural fertility such as the Maloca do Flechal region, where the traditional systems are slash-and-burn and shifting cultivation (Schaefer, 1997). The conflicts between natives and colonizers in the Raposa Serra do Sol Indigenous Reserve area, combined with the official policy of settlements along the Manaus–Venezuela road, have led to an ongoing trend of southward migration of settlers to occupy native forest areas.

Biomass burning due to traditional slash-and-burn is one of the main mechanisms by which carbon is transferred from the soil to the atmosphere in the Amazon region, in both Indian and settlers areas. On the other hand, maintenance of the carbon stocks is of fundamental importance for sustainable soil use. However, burning is a widespread system of soil use in the Amazon. In low fertility soils, when declining production levels are quickly reached, soils are abandoned and new areas are incorporated for production. Under

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present practices of shifting cultivation, native Indians have shortened fallow periods indicating physical and chemical degradation of all soils.

In northeastern Roraima, there are many areas of mafic rock outcrops with soils of high natural fertility that could, in principle, support exploitation pressure for a longer period compared with other soils of the vicinity. One such area is the Indian Maloca do Flechal. There, however, other limitations, such as a higher magnesium–calcium ratio, steep slopes and low phosphorus availability can occur (Schaefer et al., 1993; Schaefer and Dalrymple, 1995).

Because of the climatic variation in the Amazon region over geological time, northeastern Roraima changed from a sub-recent period of semi-arid climate to present-day conditions of greater precipitation (Schaefer, 1994; Schaefer and Vale Júnior, 1997), indicating an advance in chemical weathering and erosion processes that contributed to a greater risk of soil degradation. These processes can acquire irreversible features if soils are incorrectly managed. Field observation allowed inferences on the advance of the negative impacts of some human actions, such as gold mining in terraces along streams, and widespread, insufficient fallow periods for subsistence agriculture.

According to the RADAMBRASIL project report (Brasil, 1975) these soils are not suitable for intense pasturing and agricultural use because of steep slopes, rock outcrops and shallow profiles. The conservation of these lands is conditioned by the native population pressure that, presently, limits exploitation only to the smooth, flat and low lying areas along the valleys. The more hilly areas are occupied with natural pasture and are submitted to a constant burning process. The objective of this study was to examine the chemical and physical attributes and discuss the sustainability of soils developed from chemically-rich rock in northeastern Roraima, exploited by the local native Indians at least since the 19th century.

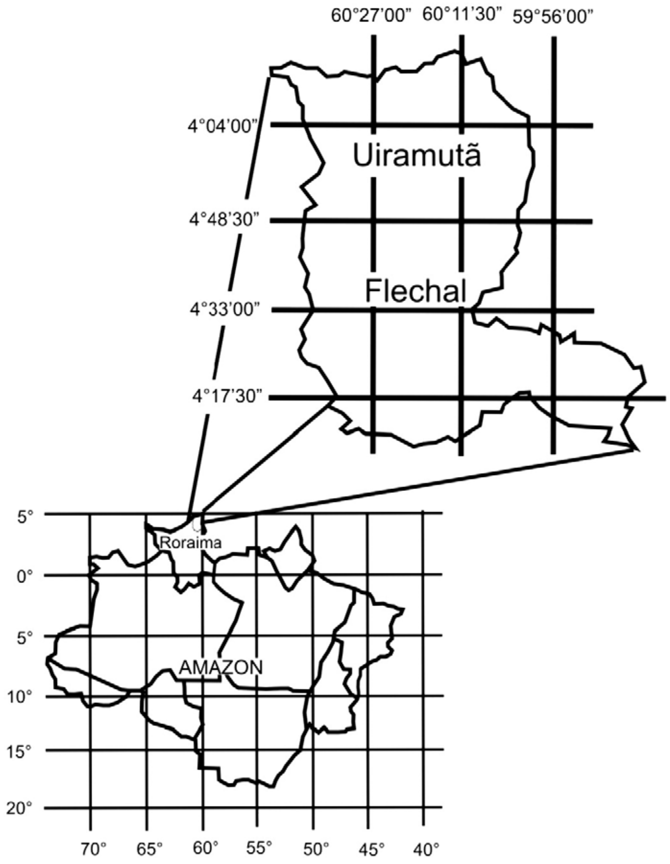

Fig. 1. Location of the studied area.

2. Material and methods

2.1. Description of the area and sample collection

The area under study is located at Maloca do Flechal, in the Uiramutã County, northeastern Roraima. It is part of the Raposa–Serra do Sol Reserve, and stretches between 4° 25′ and 4° 45′N and 60° 15′and 60° 20′ W (Fig. 1). The local geology consists of the Pedra Preta Formation, belonging to a mafic suite (Avanavero magmatics), chiefly diabase, diorites and gabbros, which occur as sills interbedded in the Roraima Quartzites. There is a tall deciduous to semi-deciduous forest development on soils derived from mafic rocks, contrasting with very shallow and chemically poor soils on quartzite, covered by open savanna (Schaefer, 1997). This mafic dyke stretches from the Amazon–Orinoco interfluve plateau to the Guyana–Brazil border, ranging from 600 m to more than 1200 m of altitude. The climate is characterized by two well-defined seasons and rainfall around 1500 mm per year (Pinheiro, 1990), reaching less than 1200 in places.

The shifting agriculture in the Flechal community, as well as in the nearby Bananeira and Nova Vida malocas, is based on the cultivation of beans (Feijão flechal, *Phaseolus vulgaris*), maize, cassava, banana, coffee and other orchard garden crops. The most used soils are those locally named 'eri-k'tum', dark-colored chernosols, under gentle relief and lower altitudes (600 m), where maize/beans consort and cassava are dominant. The Indian bean variety "Flechal" is a commercial crop, although productivity is low in average (300 kg ha^{-1}). In the Nitosols, at higher altitude (800 m) under undulating relief, maize, cotton and beans are cultivated. In Table 1, vegetation, land use, relief and erosion risks are described for each soil class in the area.

Soil samples were collected along an east–west soil catena following the outcrops of the main mafic body, observing geomorphological aspects, as well as native land use and applied management, selecting areas with natural pasture and subsistence agriculture (slash-and-burn) for more than 20 years by local Indians. The samples were air-dried in the laboratory, sieved in 2 mm mesh to obtain the air-dried fine earth. This was then submitted to physical and chemical analysis followed by analytical procedures, described below.

2.2. Physical, chemical and mineralogical analyses

The textural analysis of the soils was performed by quantifying the coarse and fine sand, silt and clay, dispersed clay in water and degree of flocculation, according to Embrapa (1997).

The pH was determined in water and in 1 mol L^{-1} KCl solution by a potentiometer using a 1:2.5 (v/v) ratio of soil/solution. The exchangeable cations, extracted by 1 mol L^{-1} KCl (Ca^{2+} and Mg^{2+}), were determined by atomic absorption spectrometry. The Al^{3+}, extracted by 1 mol L^{-1} KCl, was volumetrically determined by 0.025 mol L^{-1} NaOH titulometry. The potential acidity (H + Al) was determined by extraction with 0.5 mol L^{-1} calcium acetate at pH 7.0 and quantified by NaOH titulometry (Embrapa, 1999). The P, K and Na elements were extracted using the Mehlich-1 extractor and determined by flame photometry (K and Na) and colorimetric method (P). From the results obtained the sum of bases

Table 1
Soils, relief, present land use, erosion risk and vegetation.

Soil	Relief	Land use	Erosion risk	Vegetation
Eutrophic Red Nitosol	Undulating	Native pasture and annual crops	Very high	Grass/seasonal forest
Chernosols	Flat to gently undulating	Beans, cassava, maize, coffee, fruits	Medium	Seasonal forest
Eutric Cambisols	Undulating	Native pasture and annual crops	High	Grasses and seasonal forest

Table 2
Morphology and classification of the Maloca do Flechal soils.

Perfil	Classification	Horizon	Depth	Münsell color		CS	FS	Silt	Clay	WDC	FD	Silt/Clay	Textural classes
			.....cm....	......Dry.....	.....Wet.....	....................%......................							
1	Eutrophic Red Nitosol — NVe	Ap	0–10	7.5 YR 4/4	7.5 YR 3/3	9	11	28	52	22	57	0.54	Clayey
		Bnitic$_1$	10–25	7.5 YR 5/6	5 YR 4/4	10	11	26	53	27	48	0.49	Clayey
		Bnitic$_2$	25–60+	5 YR 5/6	2.5 YR 4/6	04	06	26	64	0	100	0.41	Very clayey
2	Orthic Ebanic Chernosol — Meo	Ap	0–32	7.5 YR 4/2	2.5 YR 5/1	22	27	23	28	09	69	0.82	Sandy clay loam
		Bnitic$_1$	32–50	10 YR 4/3	10 YR 3/2	27	28	21	24	13	43	0.87	Sandy clay loam
		Bnitic$_2$	50–90+	10 YR 5/4	10 YR 4/4	11	18	34	37	21	44	0.92	Clay loam
3	Eutrophic Tb Haplic Cambisol — CXbe	Ap	0–20	7.5 YR 3/2	7.5 YR 3/2	19	15	34	32	9	70	1.06	Clay loam
		Bi$_1$	20–35	7.5 YR 3/2	7.5 YR 3/2	10	13	31	46	22	52	0.67	Clayey
		Bi$_2$	35–60+	7.5 YR 4/4	7.5 YR 3/3	11	9	33	47	26	44	0.70	Clayey
4	Orthic Ebanic Chernosol — Meov	Ap	0–20	7.5 YR 4/1	7.5 YR 3/1	30	12	29	29	15	49	1.00	Clay loam
		Bi$_1$	20–38	10 YR 4/1	10 YR 4/2	27	13	22	38	33	30	0.58	Clayey
		Bi$_2$	38–58	10 YR 5/3	10 YR 5/2	35	15	21	29	18	37	0.72	Sandy clay loam
		BC/Cr	58–90+	10 YR 6/3	10 YR 5/4	33	8	31	28	20	28	1.11	Clay loam
5	Eutrophic Tb Haplic Cambisol — CXbe	Ap	0–30	10 YR 4/4	10 YR 3/3	20	17	28	35	15	57	0.80	Clay loam
		Bi$_1$	30–83	7.5 YR 4/6	5 YR 4/4	28	12	31	29	23	20	1.07	Clay loam
		Bi$_2$	83–111	7.5 YR 4/6	5 YR 4/4	13	12	37	38	29	24	0.97	Clay loam
		Bi$_3$	111–163	5 YR 4/4	2.5 YR 3/6	5	10	30	55	39	28	0.54	Clayey

Ap — plowed horizon, Bi — cambic horizon, CS — bnitic–nitic horizon, coarse sand; FS — fine sand; WDC — water dipersible clay; FD — flocculation degree; V — vertic.

(SB), total (T) and effective (t) cation exchange capacity, base saturation (V%) and aluminum saturation were calculated.

The mineralogy was investigated by X-ray diffraction of the clay and silt fraction. From the natural, Fe-free clay fraction, oriented slides were prepared and irradiated in an X-ray diffractometer at sweeping angle (2θ) intervals between 2° and 40° and a goniometer speed of 2° in 2θ/min, using $CuK\alpha$ radiation with Ni filter (Whittig and Allardice, 1996). Powdered silt slides were analyzed under the same conditions. The diffraction patterns were interpreted according to Chen (1977). The amorphous iron oxide from the surface horizons was extracted using ammonium oxalate, while the content of free Fe-oxides was extracted by the Dithionite–Citrate method (DC) in three successive extractions (McKeague and Day, 1966). The determinations were made by ICP spectrometry in a Perkin Elmer spectrometer model 3300 DV. The crystalline Fe was calculated by the difference between the Fe extracted by DC (Fed) and the Fe extracted by ammonium oxalate (Feo).

The Zn, Cu and Mn in the fine earth were determined by total digestion in an Etnos Plus Microwave Labstation oven controlled by the Easywave software for Windows, under pressure and temperature range of 30 °C to 180 °C for 5 min for stability and at 210 °C for 25 min at a 700 W potency. The digestion was carried out with 5 ml HCl, 5 ml HNO_3 and 8 ml of HF in 0.5 g soil, and the metal contents were determined by ICP.

The remaining P was determined by the methodology described by Alvarez V. et al. (1988). The maximum phosphate adsorption capacity (MPAC) for some selected soil horizons was determined in triplicate according to the P-remaining levels, according to the methodology proposed by Alvarez V and Fonseca (1990). Data were adjusted to the Langmuir non-linear model to obtain the relationship between the concentration of adsorbed P per unit of adsorbent (soil) and the P concentration in the equilibrium solution. The maximum capacity of adsorption (b) and the coefficient of adsorption energy (a) were calculated.

3. Results and discussion

3.1. Classification and physical properties

The soils were classified according to the Brazilian Soil Classification system (Embrapa, 2006) and translated to English. Within the study area the eutrophic Red Nitosol is present on steep slopes, while eutric, vertic Chernosols and Cambisols are dominant in the low landscape positions.

The soils were classified as Eutrophic Red Nitosol (Alfisol), Orthic Ebanic Chernosol (Mollisol), Eutrophic Tb Haplic Cambisol (Mollisol), Orthic Ebanic Chernosol (Mollisol) and Eutrophic Tb Haplic Cambisol (Mollisol) (Table 2). The first two are not typical of the Amazon region. The presence of Mollisols in this area may reflect a drier paleoclimate but persistence under present climatic conditions clearly relates to the presence of mafic rock parental material. Similar soils have been reported from elsewhere in the Amazon related to basalt outcrops and seasonal climates (Falesi, 1972; Falesi et al., 1986; and Schaefer et al., 1993). Reddish soil colors were observed with depth in the soil profiles P1 (Nitossol), and P5 (Cambisol). The soil profile P5 (Cambisol) presented a varied color pattern, with strong reddening in the Bi3 horizon. This subsurface reddening is widespread in the upper, drier parts of Serra do Sol Reserve, and reveals a past drier condition, less influence from organic matter and a greater presence of hematite (Schwertmann, 1966). This effect is consistent with the amount of crystalline Fe determined by the Dithionite–Citrate extraction (Fed), Table 6.

The texture ranges from sandy clay loam on the surface to very clayey in the Chernosols' subsurface, and greater silt. The Chernosols and Cambisols show a high silt to clay ratio, which suggests higher nutrient reserves and relatively low degree of weathering (Table 2). The predominant clayey texture, and low sand content of these soils are related to the mafic rock composition, with little quartz. The higher amounts of clay of the Nitosol indicate a greater degree of weathering.

Table 3
Mineralogical composition of the clay, silt and sand fractions of the soils studied by X-ray diffraction.

Profile	Soil	Horizon	Clay	Silt	Sand
1	NVe	Ap	Ct, Gt	Qz, Ct, Bt, Fs, Ilm	Qz, Mi
		Bnitic$_1$	Ct, Gt	Qz, Ct, Bt, Fs, Ilm	–
		Bnitic$_2$	Ct, Il, Gt	Qz, Ct, Bt, Fs, Ilm, Pg	Qz, Mi,
2	MEo	Ap	Ct, Il, Gt	Qz, Bt, Fs, Px	Qz, Mi
		Bnitic$_1$	Ct, Il, Gt	Qz, Mi, Fs, Ct, Px	–
		Bnitic$_2$	Ct, Il, Gt	Qz, Ct, Mi	Qz, Mi
3	CXbe	Ap	Ct, Il/Mt, Es,Gt	Qz, Fs, Ct, Px, Af	Qz, Fs, Pg, Mi
		Bi$_1$	Ct, Il, Es	Qz, Fs, Pg, Af, Ct	Qz, Fs, Pg, Mi
		Bi$_2$	Ct, Il, Es	Pg, Fs, Qz, Ct, Mi, Af	Pg, Qz, Fs, Mi, Mg
4	MEov	Ap	Ct, Il, Es	Fs, Pg, Qz, Ct, Mi, Af	Qz, Pg, Af, Fs
		Bi$_1$	Ct, Il, Es	Qz, Ct, Fs, Mi, Il, Pg, Af	Qz, Af, Pg, Fs
		Bi$_2$	Es, Ct, Il	Ac, Cl, Mi, Fs	–
		BC/Cr	Ct, Es, Il	Qz, Ct, Il/Mi, Fs, Pg, Af	Qz, Pg, Fs, Cn
5	CXbe	Ap	Ct, Il, Gt	Ct, Qz, Zl, Pg	Qz, Fs, Ru
		Bi$_1$	Ct, Il, Gt	Qz, Ct, Fs, Pg	–
		Bi$_2$	Ct, Il, Gt	Ct, Qz, Hb, Bt	Qz
		Bi$_3$	Ct, Il, Gt	Qz, Ct, Mi/Il	–

Qz — quartz, Ct — kaolinite, Gt — goethite, Bt — biotite, Fs — feldspars, Ilm — ilmenite, Mi — mica, Pg — plagioclase, Af — amphibole, Px — pyroxene, Il — illite, Mt — montmorillonite, Es — smectite, Bt — biotite, Ac — actinolite, Cl — chlorite, Cn — corindon, Zl — zeolite, Hb — hornblende, Ru — rutile, Gb — gibbsite, Hm — hematite, Mg — manganite.

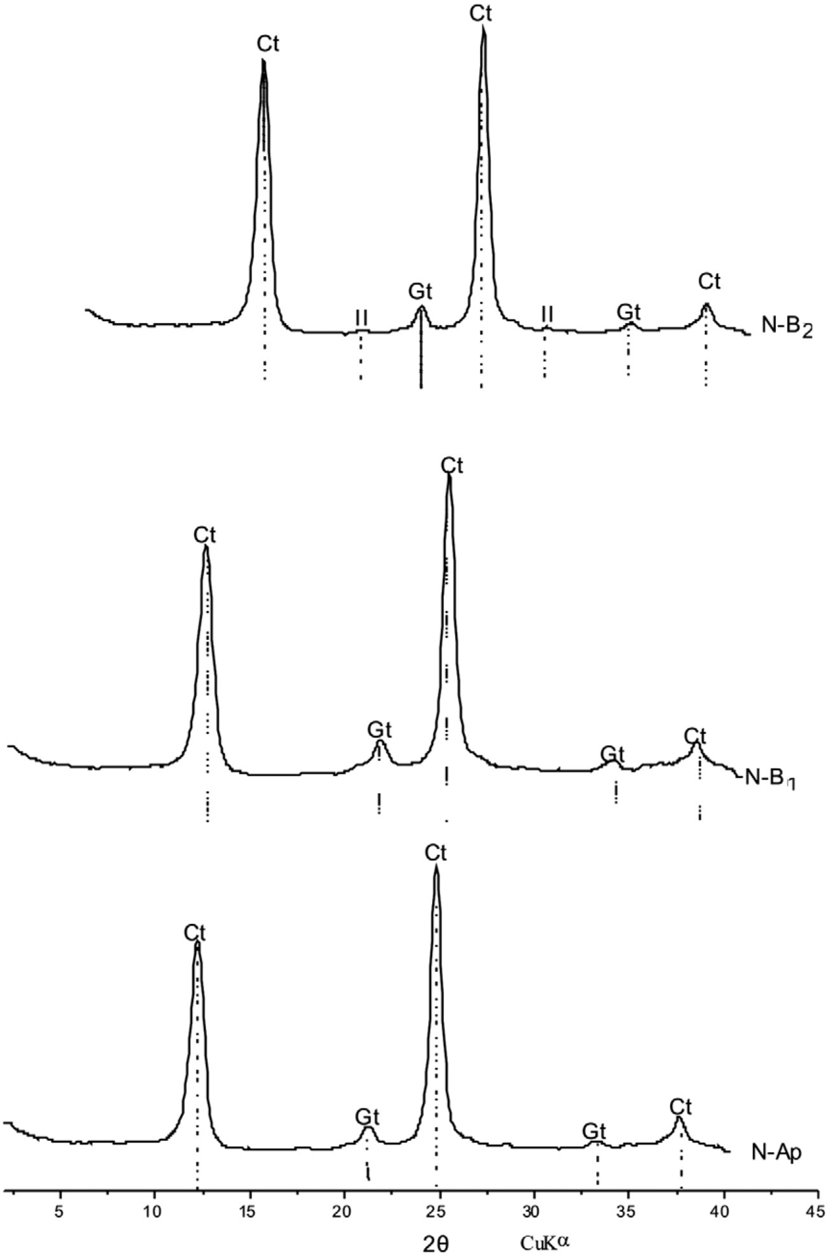

Fig. 2. X-ray diffractogram of the natural clay fraction in the horizons corresponding to profile 1 (Red Nitosol). Ct—kaolinite, Gt—goethite, Il—illite.

The soil structure varies from small subangular blocky in the Nitosols, to medium to large angular blocky in the Chernosols. The presence of the vertic features in soil profile P4 is marked, with block and prismatic structures with slickensides in the Bi horizon. The unusual mountainous/hilly relief of this part of Brazilian Amazonia imparts great soil variation over a short distance. The texture, topography and lower flocculation degree of the Nitosol favors the loss of suspended clay under heavy rainfall, which determines the widespread occurrence of severe erosion, and truncated soils. Nunes et al. (2001) also observed this process while studying soils with argillic/nitic B horizons in the hilly landscape of "Mar de Morros in Minas Gerais".

3.2. Mineralogical soil composition

The soil mineralogy was conditioned to the landscape position. The Red Nitosol shows a kaolinite/goethite mineralogy, formed on the flat summit, while the Chernosol and Cambisol with 2:1 clay minerals occupy the lower parts of the landscape (Table 3). Soils that developed from mafic parent material, and possessing 2:1 clays were previously studied by Schaefer et al. (1993) in Roraima; in the lowland, humid area of the Taiano Agricultural Colony, they showed a typically kaolinite and oxidic mineralogy of the clay fraction (Vale Júnior, 2000), due to a wetter climate. The climate around Maloca do Flechal is more seasonal, and experienced even drier paleoclimates (Schaefer and Dalrymple, 1995; Schaefer and Vale Júnior, 1997). Although quartz was present in all soils, these soils possess considerable amounts of easily weatherable minerals in the silt fraction, helping to maintain high soil fertility, through the slow release of nutrients such as calcium, magnesium and potassium.

The X-ray diffraction (Table 3 and Figs. 2–6) shows the kaolinite mineralogy in the clay fraction of the soils with the presence of 2:1 clays in profiles 3 and 4. This is morphologically expressed by the presence of cracks due to expansive minerals, notably in profile 4. Except for the Nitosol, illite was present in the clay fraction of virtually all soils. The present-day increasing weathering under increasing rainfall may be contributing to the current instability of the 2:1 clay

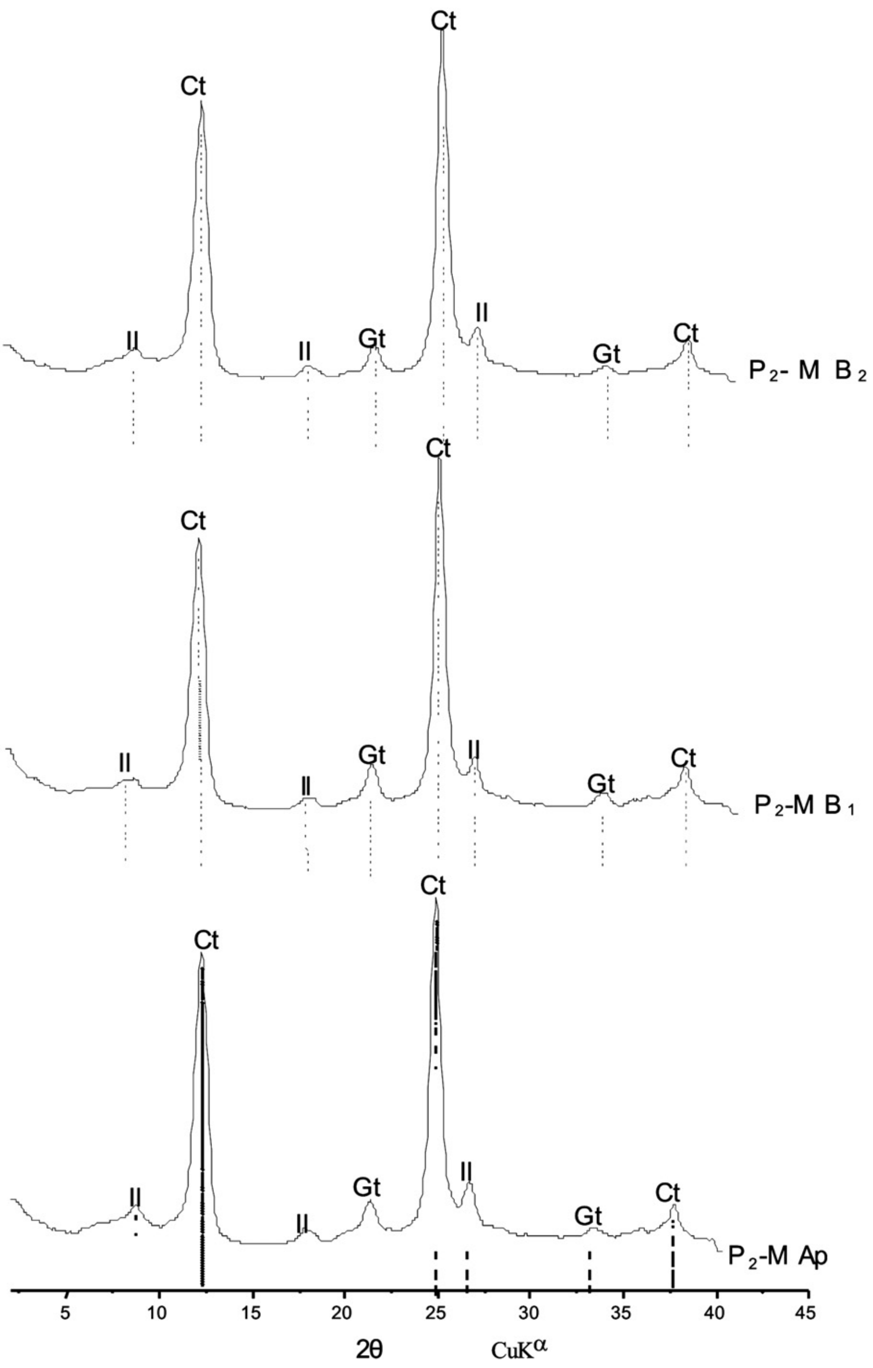

Fig. 3. X-ray diffractogram of the natural clay fraction in the horizons corresponding to profile 2 (Chernosol). Ct—kaolinite, Gt—goethite, Il—illite.

minerals in the Chernosols. Although primary minerals occurred in the silt and sand fraction of most soils, the present environmental conditions favor the formation of kaolinite group (1:1) minerals.

3.3. Chemical characterization

Except for the Nitosols, the soils were characterized by a high base saturation percentage, neutral pH or low acidity (Table 4). All soils presented negative ΔpH values (pH KCl − pH H_2O), indicating a negative charger. Furthermore, soil profiles P3, P4 and P5 had pH > 7, which may have a negative effect on the availability of micronutrients such as boron, zinc, iron and manganese (Miller and Donahuer, 1999) and, also, the availability of phosphorus through the formation of low solubility P-calcium compounds (Ryan et al., 1985; Novais and Smyth, 1999).

In the studied soils with Chernozemic A horizon, calcium predominated in the exchange complex, and the Ca^{+2}/Mg^{+2} ratio differed from the levels obtained by Schaefer et al. (1993), who reported magnesium content greater than calcium in soils with Chernozemic A derived from other mafic rocks in this part of Roraima. These findings highlight the variability of low-weathered soils of this indigenous area.

Despite the presence of illite and a relatively low weathering degree, the levels of exchangeable potassium and Melich 1 soil test phosphorus were low in all soils. Under continued cultivation, these elements would be rapidly depleted and exhausted, requiring supply by fertilizer application, at a high economic cost. The low phosphorus content in

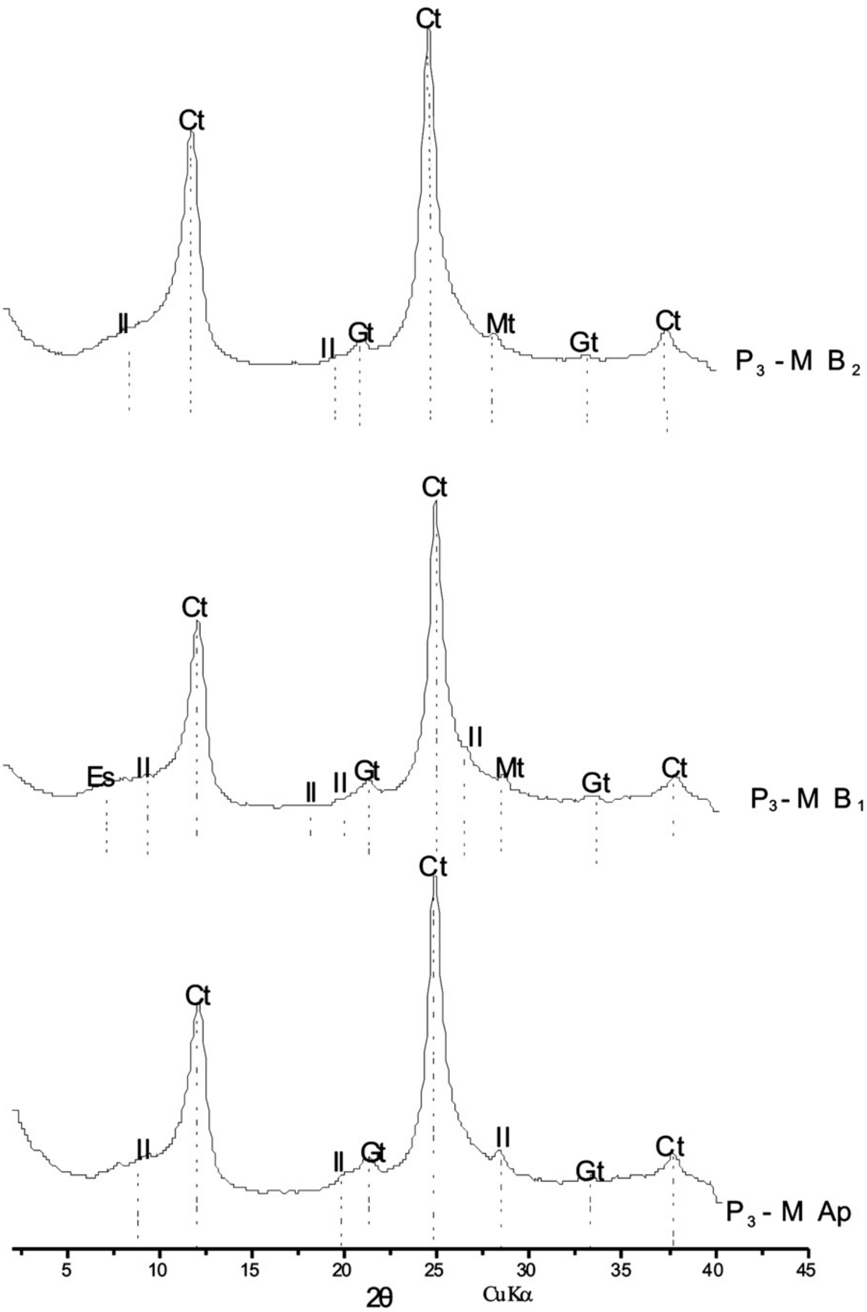

Fig. 4. X-ray diffractogram of the natural clay fraction in the horizons corresponding to profile 3 (Cambisol). Ct—kaolinite, Gt—goethite, Il—illite, Sm—smectite, Mt—montmorillonite.

soils of the Amazon region is a widespread feature (Sanchez, 1976 and Smyth, 1996). Exceptional higher P levels are found only in anomalous areas with a large input of richer allocthonous sediments, such as in the waterlogged floodplain of the Amazon River, or in small patches of anthropogenic soil resulting from pre-Colombian settlements, named Indian Black Earth (Schaefer et al. 2000; Lima et al., 2002). The low phosphorus levels in these soils are due to the low levels of minerals such as apatite in the parent rock, which is an exception in the mafic rocks of the Amazon as a whole (Brasil, 1975; Schaefer et al., 1993) or Amazonian Dark Earths (Woods and McCann, 1999; Woods and Glaser, 2004; Lehmann et al., 2003; Falcão et al., 2009). Total phosphorus content in soils developed from diabase is usually high elsewhere in Brazil.

Clay activity higher than 27 $\text{cmol}_c\ \text{kg}^{-1}$ in the Chernosols partially resulted from the contribution of soil organic matter. After discounting the carbon contribution in the formula, $\{\text{Tr} = [T - (4.5 \times \text{Corg})/\%\ \text{Clay}] \times 100\}$, the calculated clay activity was relatively lower than that required for this soil class. Only the B horizon of the Chernosol, with vertic characteristics, has CEC values in the range of high activity clay, consistently with the montmorillonite identified in Fig. 4, that increases CEC. This also highlights the contribution of the organic matter to the exchange complex of these soils (Stevenson, 1994).

The clay activity in the Chernosols shows the current level of leaching of these soils after the onset of wetter pedoclimatic conditions in this part of the Amazon (Schaefer and Dalrymple, 1995). Hence, high charged 2:1 minerals become unstable and weather to either kaolinite or low charge 2:1 intergrade minerals (Borchardt, 1989; Schaefer et al., 1993).

3.4. Fe forms extracted by Dithionite–Citrate (Fe-DC) and Fe and Si extracted by ammonia oxalate in the clay fraction

The soluble Fe contents obtained by DC cumulative extractions (Table 5) ranged from 28.40 g kg^{-1} in the vertic Chernosol to

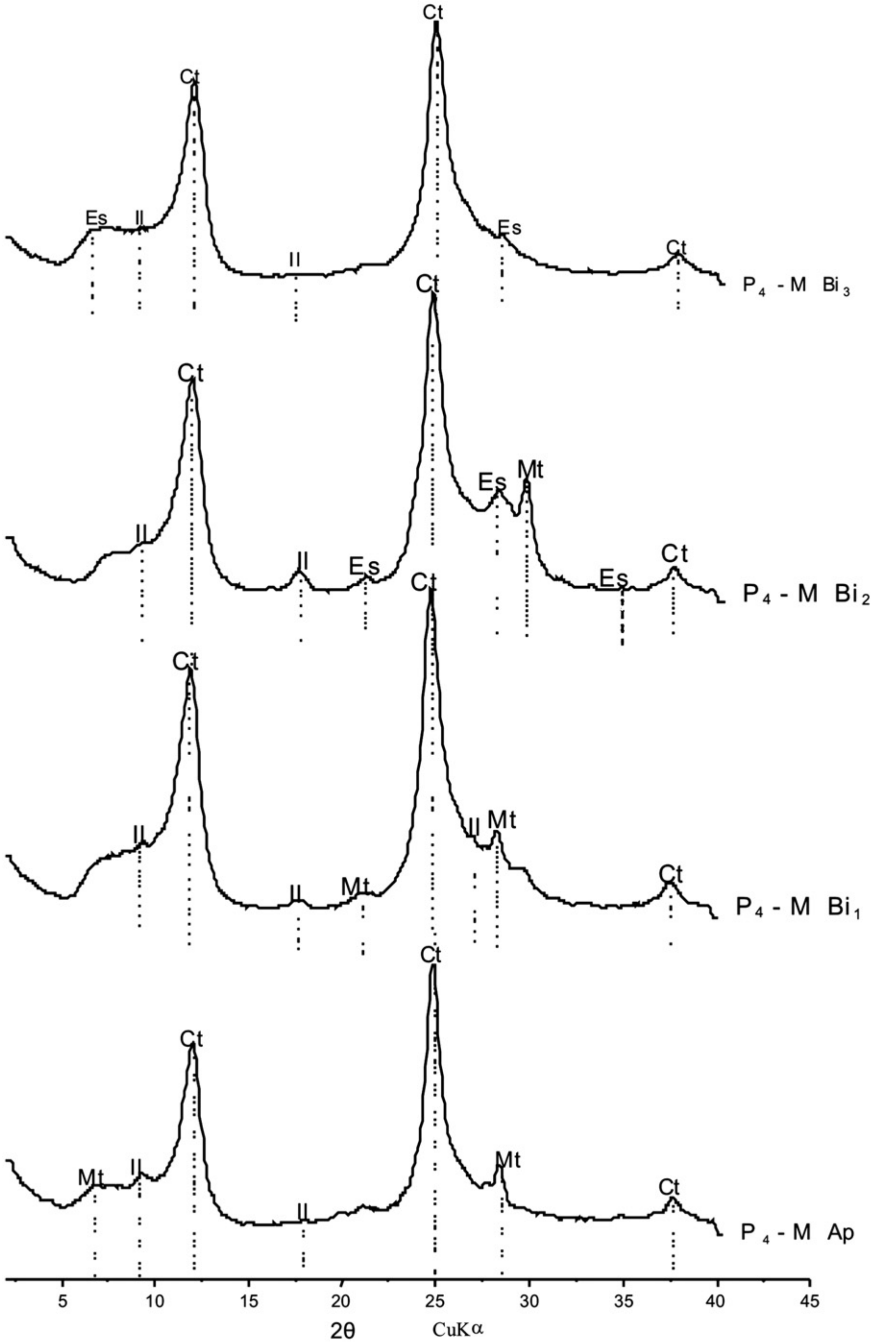

Fig. 5. X-ray diffractogram of the natural clay fraction in the horizons corresponding to profile 4 (vertic Chernosol). Ct—kaolinite, Il—illite, Sm—smectite, Mt—montmorillonite.

115.40 g kg^{-1} in the Cambisol (P5). Except for the Nitosol, all others have easily extractable Fe forms, which were virtually exhausted after three extractions. Schaefer et al. (1993) obtained comparable results when working with similar soils in nearby areas. In the Nitosol there was an increase in free Fe with depth, unlike the other soils, where levels tended to decrease with depth. The Cambisol (P5) followed the decreasing tendency down to the Bi2 horizon. However, the Bi3 horizon showed a much higher Fe iron level than the overlying horizon, as a result of its higher degree of evolution. These values are consistent with the soil evolution degree, that is, greater Fe^{3+} levels in deeper soils are associated with a greater degree of weathering. The Feo/Fed ratio further illustrates the degree of soil evolution.

The data on oxalate extractable silica revealed differences related to the soil types. Highly weathered soils, such as the Nitosol, presented lower levels because their oxide mineralogy was revealed by X-ray diffraction, due to silica leaching in the environment. Considering that the soluble silica concentration in soils ranges from 1 to 40 mg L^{-1} (McKeague and Cline, 1963; Elgawhary and Lindsay, 1972), the observed levels suggest that much of the silica is amorphous. The total silica content ranges from 400 g kg^{-1} for sandy soils to 8 g kg^{-1} for highly weathered tropical soils (Tisdale et al., 1985). The greater silica levels in both Cambisol and Chernosol profiles (P3 and P4) were due to the current Si release from weathering of 2:1 minerals and silt fraction, under higher pH, in enhancing silicate dissolution with silica losses.

3.5. Total Zn, Cu and Mn content

In the Nitosols the total zinc contents decreased with depth (Table 6). Bearing in mind that the pH of these soils is acid (<6), this

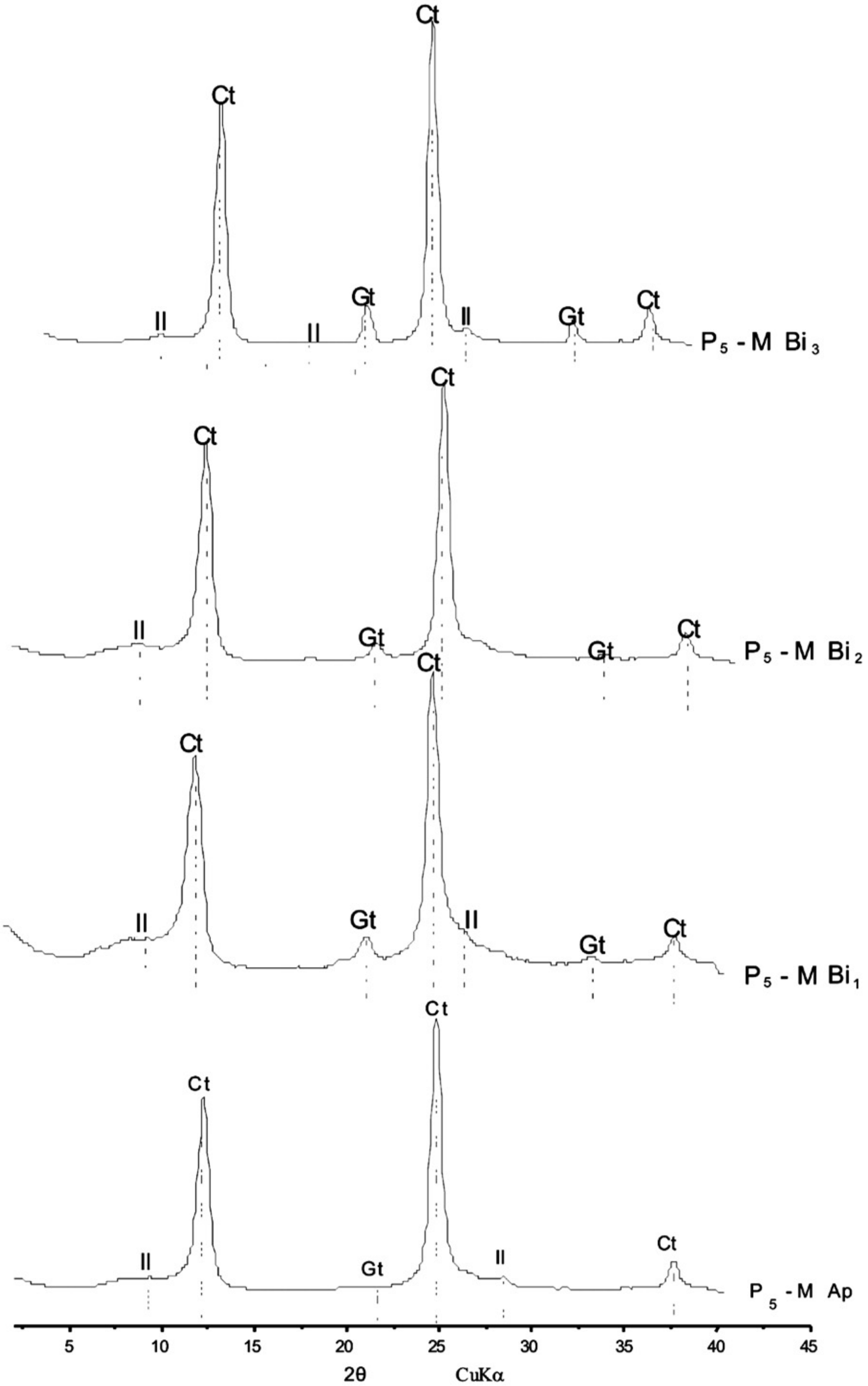

Fig. 6. X-ray diffractogram of the natural clay fraction in the horizons corresponding to profile 5 (Cambisol).

metal is more strongly complexed with the organic compounds (Alloway, 1997), and a large portion may be associated with organic matter.

Copper contents are a function of the parent material and soil weathering (Jarvis, 1981). Consistently, we observed that the most weathered soils showed lower copper contents. However, due to the pH and mineralogy of these soils, copper availability is likely. Similar to zinc, the more weathered soils showed decreasing copper with depth, illustrating the importance of nutrient cycling and organic matter in retaining micronutrients. Manganese did not show a well-defined relationship with depth, being more abundant than copper and zinc due to its close affinity with Fe in mafic rocks (Resende et al., 1995).

3.6. Phosphorus status and P adsorption capacity (PAC)

The different P concentrations used allowed maximum phosphorus adsorption capacity (MPAC) to be reached, as can be observed from the MPAC levels (Table 7) and from the adjusted curve of Langmuir isotherm (Figs. 7–9). The MPAC ranged between 0.321 and 2.380 mg g^{-1}. The Nitosol showed the greatest MPAC, 1.547 mg kg^{-1}, which can be attributed to clay content and soil mineralogy, represented by high contents of iron oxides (Rolim-Neto et al., 2004). The lowest adsorption levels were observed in the Chernosol and Cambisol. In this case, where the A and B horizons were considered, there was increasing adsorption with soil depth.

Table 4
Chemical characteristics of the soils derived from mafic rocks in the Maloca do Flechal region.

Soil	Horizon	PH		C	Al^{+3}	H + Al	Ca^{+2}	Mg^{+2}	K^+	Na^+	SB	*t*	*T*	Tr	Tr–C	*V*	*m*	*P*
		H_2O	KCl	dag kg^{-1}	$cmol_c$ kg^{-1}											%		mg kg^{-1}
NVe	Ap	5.7	4.3	24.6	0.05	6.87	2.63	2.48	0.10	0.13	5.34	5.39	12.21	23.5	2.2	43	1	0.96
	$Bnitic_1$	5.5	4.1	15.6	0.27	5.66	1.21	0.98	0.03	0.05	2.27	2.54	7.93	15.0	1.7	28	11	0.77
	$Bnitic_2$	5.9	5.1	09.3	0.00	2.20	1.03	0.91	0.01	0.03	1.98	1.98	4.18	10.0	3.43	65	0	0.72
MEo	Ap	6.1	5.2	23.8	0.00	4.34	6.87	3.16	0.15	0.32	10.50	10.50	14.84	53.0	14.8	71	0	2.50
	$Bnitic_1$	6.1	4.5	17.2	0.05	4.51	5.01	2.38	0.13	0.18	7.70	7.75	12.21	50.9	18.6	63	1	1.46
	$Bnitic_2$	6.2	4.6	14.2	0.05	3.57	5.80	2.62	0.05	0.04	8.51	8.56	12.08	32.8	15.5	71	1	1.01
CXbe	Ap	6.8	4.9	15.3	0.05	2.75	8.69	2.79	0.05	0.11	11.64	11.64	14.39	45.0	23.5	81	0	1.33
	Bi_1	7.2	5.1	10.8	0.00	2.09	9.05	0.30	0.04	0.11	9.50	9.50	11.59	25.2	14.6	82	0	1.25
	Bi_2	7.3	5.4	9.5	0.00	1.54	9.21	0.00	0.05	0.12	9.38	9.38	10.92	23.2	14.1	86	0	1.44
MEov	Ap	7.0	5.0	20.6	0.00	2.53	9.31	0.04	0.05	0.09	9.35	9.35	11.88	41.5	9.5	79	0	1.16
	Bi_1	7.3	4.9	6.9	0.00	1.37	10.50	0.08	0.07	0.14	10.79	10.79	12.16	21.6	15.0	86	0	1.46
	Bi_2	7.4	4.4	3.7	0.00	1.43	12.7	0.06	0.05	0.11	12.92	12.92	14.35	49.5	43.7	90	0	1.39
	BC/Cr	7.6	5.2	4.0	0.00	0.99	7.10	0.43	0.07	0.15	7.75	7.75	8.74	31.2	24.8	89	0	1.37
CXbe	Ap	6.5	4.9	19.3	0.00	3.24	6.75	0.37	0.04	0.07	7.23	7.23	10.63	29.9	5.1	69	0	1.22
	Bi_1	7.3	5.2	5.9	0.00	1.48	7.44	0.46	0.03	0.08	8.01	8.01	9.49	32.7	23.6	84	0	1.26
	Bi_2	7.8	5.9	3.7	0.00	0.71	7.31	0.00	0.03	0.09	7.43	7.43	8.14	21.4	17.0	91	0	1.08
	Bi_3	8.0	6.6	4.2	0.00	0.16	3.59	0.29	0.02	0.05	3.95	3.95	4.11	7.5	4.0	96	4	0.92

Tr = total clay activity; TR–C — clay activity minus carbon contribution.

The MPAC correlated positively with clay content (Fig. 10), consistent with findings of Silva (1999) and Lima (2001), in different Amazon soils from Acre and Amazonas states, respectively. The importance of clay type and amount for the adsorption phenomenon was recognized by several authors (e.g. Juo and Fox, 1997; Novais et al., 1991). From these results, it is possible to infer the influence of the clay nature in the phosphate adsorption phenomenon. Soils such as the Nitosol, which have an oxidic clay mineralogy, display a higher adsorption capacity. This highlights the importance of the specific surface and soil mineralogy for phosphate adsorption. Although adsorption increased with soil depth, at the same time as the TOC contents decreased, it was not significantly correlated with the total organic carbon content. Also, adsorption was not correlated with dithionite-extractable Fe, as might be expected (Table 7). In principle, low phosphate adsorption capacities would be expected in these soils. This is of fundamental importance as they have very low phosphorus content and local agriculture depends on high cost imports of this nutrient from distant sources.

Table 5
Analytical results of the dithionite citrate and oxalate soluble iron content and of oxalate soluble silica in soils developed from mafic rocks in the Maloca do Flechal region.

Soil	Horiz.	Dithionite (Fed)						(Feo)	Feo/Fed	Fec	SiO_2o
		1^a	2^a	3^a	4^a	5^a	Total				
		g kg^{-1}								g kg^{-1}	
NVe	Ap	46.4	11.2	0.7	–	–	58.3	3.5	0.06	54.8	1.41
	$Bnitic_1$	57.2	10.1	0.9	–	–	68.2	4.6	0.07	63.6	–
	$Bnitic_2$	55.4	18.4	1.6	–	–	75.5	3.2	0.04	72.3	1.13
MEo	Ap	87.1	15.3	3.6	–	–	106.0	7.7	0.07	98.3	1.26
	$Bnitic_1$	76.3	22.4	3.9	–	–	102.7	7.5	0.07	95.2	–
	$Bnitic_2$	73.4	17.9	3.7	–	–	95.1	5.6	0.06	86.9	1.90
CXbe	Ap	44.5	4.0	3.5	–	–	52.0	6.4	0.12	45.6	2.01
	Bi_1	47.5	4.7	3.4	–	–	55.6	4.8	0.09	50.8	–
	Bi_2	43.5	4.5	3.1	–	–	51.1	4.9	0.10	46.2	2.65
MEov	Ap	28.9	2.6	3.3	–	–	34.9	7.7	0.22	27.2	2.01
	Bi_1	20.7	3.8	3.9	–	–	28.4	1.7	0.06	26.7	–
	Bi_2	20.9	4.5	4.0	–	–	29.4	1.6	0.05	27.8	1.37
CXbe	Ap	68.7	05.1	3.3	–	–	77.1	7.2	0.09	69.9	1.61
	Bi_1	57.3	06.3	2.1	–	–	65.8	3.7	0.06	62.1	–
	Bi_2	56.3	08.2	0.3	–	–	64.8	2.5	0.04	62.3	2.03
	Bi_3	100.1	12.6	2.6	–	–	115.4	1.2	0.01	114.2	–

Fec — crystalline iron. SiO2o — silica extracted by oxalate. Fed — iron extracted by dithionite. Feo — iron extracted by oxalate.

4. Conclusions

The most important shifting-cultivated soils in the Indian Reserve of Raposa–Serra do Sol are Chernosols, Cambisols, Red Nitosols developed from mafic rocks, occurring in the lower slopes, steeper mid-slopes and flattened tops at the summit, respectively. They are generally clayey in surface, showing high silt levels in the Chernosols and Cambisols. The mineralogy of these unusual Amazon soils is highly variable across the landscape, varying from a kaolinite/goethite mineralogy in upslope Nitosol to a 2:1 mineralogy (Chernosols and Cambisols) downslope proportions of the catena. The weathering sequence appears related to a polycyclic genesis of the soils, in which the upland soils are related to late Tertiary/early Quaternary pedogenesis under wetter conditions, whereas downslope soils are associated with late Quaternary dry spells. The degraded 2:1 minerals

Table 6
Total micronutrient levels determined in the fine soil fraction of selected horizons of the studied soils.

Profile	Soil	Horizon	Zn	Cu	Mn
			mg kg^{-1}		
P1	NVe	Ap	49.30	96.44	142.97
		$Bnitic_2$	47.74	13.60	173.17
P2	MEo	Ap	61.78	77.31	956.15
		$Bnitic_2$	60.41	94.98	709.91
P3	CXbe	Ap	84.55	67.97	758.53
		Bi_2	79.53	50.18	1,092.93
P4	MEov	Ap	69.95	54.94	351.55
		Bi_2	66.69	70.27	794.15
P5	CXbe	Ap	78.11	109.77	492.48
		Bi_2	65.10	93.71	238.08
		Bw_1	30.68	tr	103.39

tr— trace.

Table 7
Simple linear correlation coefficients between MPAC and total organic carbon, clay percent and dithionite extracted iron.

Correlation	TOC	Clay	Fed
MPAC	-0.06^{ns}	0.87^{*}	0.59^{ns}

ns = non-significant at the 5% level of probability; * = significant at the 5% level of probability; TOC — total organic carbon; Fed = dithionite iron.

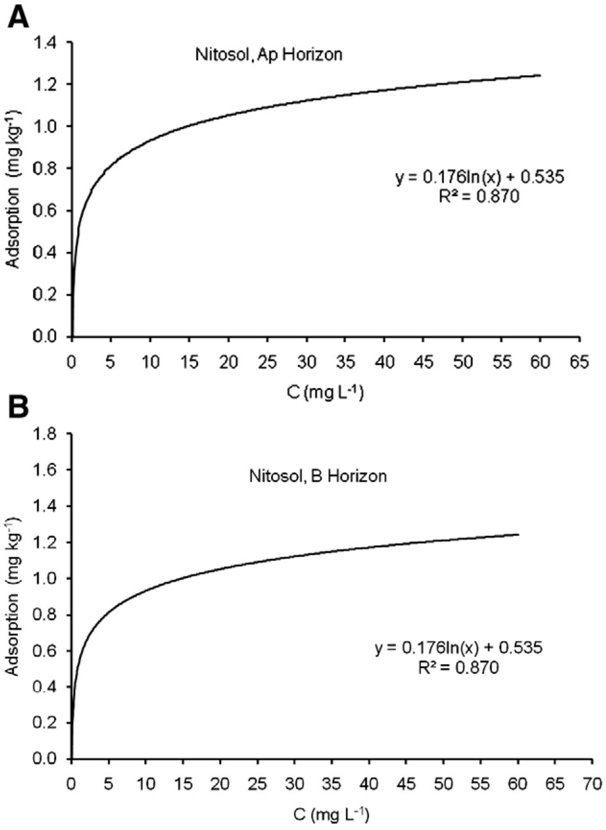

Fig. 7. (A and B) — Phosphate adsorption curves in Red Nitosol in the Maloca do Flechal region.

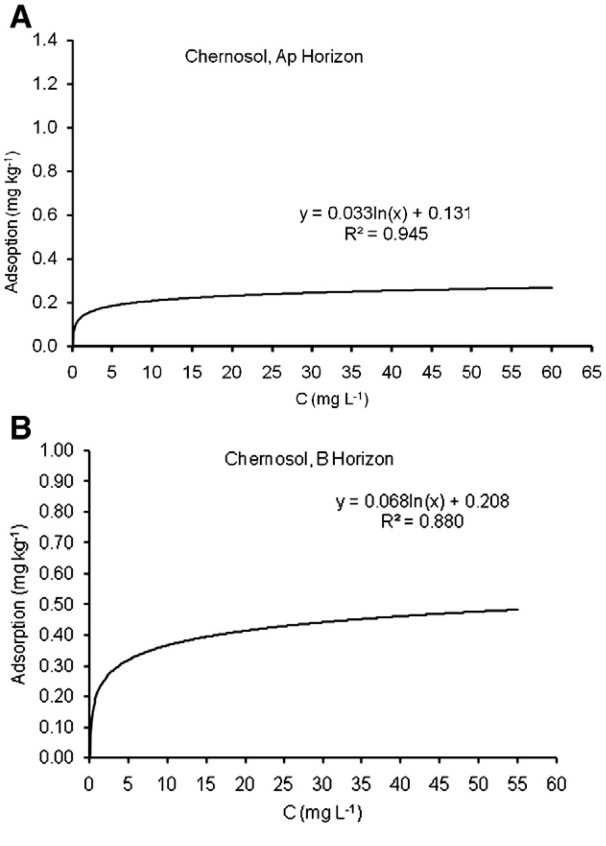

Fig. 8. (A and B) — Phosphate adsorption curves in Red Nitosol in the Maloca do Flechal region.

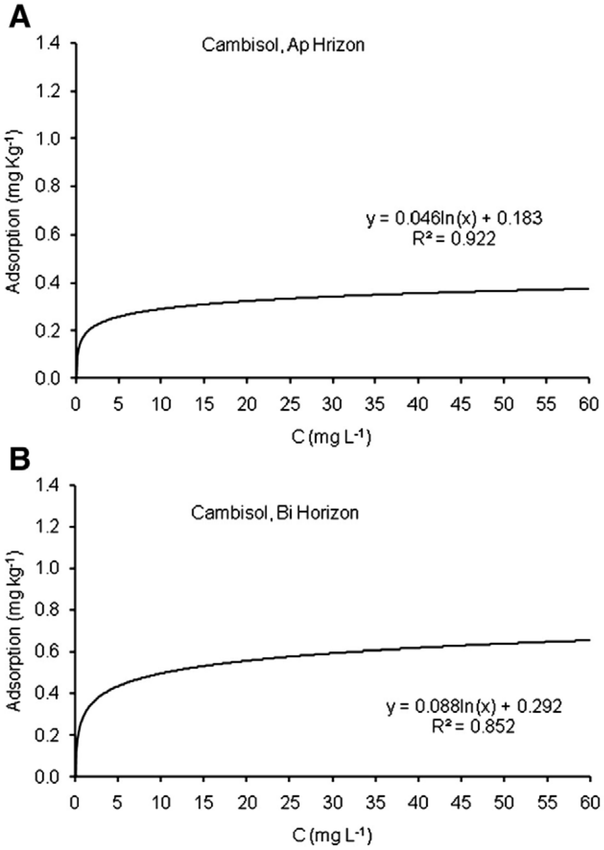

Fig. 9. (A and B) — Phosphate adsorption curves in Cambisol in the Maloca do Flechal region.

indicate soil degradation is ongoing due to present-day humid pedoclimatic conditions in this part of Amazonia.

The mid slope and lowland soils have medium to high fertility, being either cultivated or under different stages of fallow. Weathering degree is clearly shown by Fe-oxalate and Si-oxalate levels; highly weathered soil, such as the Nitosol, presented very low Fe-oxalate levels, and a high Fed/Feo ratio.

Widespread low phosphorus levels constrain soil productivity and limit shifting agriculture in a spatially limited area. The Nitosol showed a greater phosphate adsorption capacity, which is attributed to its clayey mineralogy. The Chernosols showed the lowest P adsorption, increasing with depth. Local Indian land use is based on crop diversity and intense cultivation of eutric Nitosols, Chernosols and Cambisols.

All soils under Indian cultivation display signs of physical and chemical degradation to shortened fallow under intense land use pressure. The limited land availability and increasing pressure on high

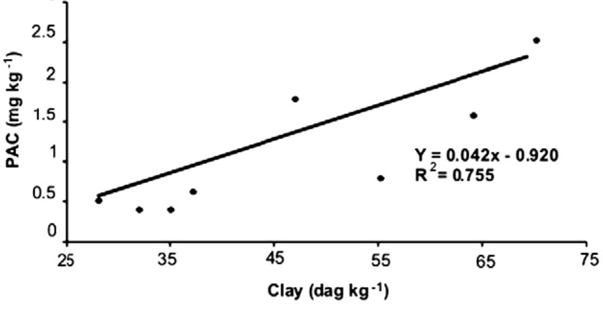

Fig. 10. PAC prediction model in function of the clay content of the studied samples, obtained by fitting a simple linear Langmuir regression equation.

fertility, fragile soils, impose serious concerns on enhanced management practices to halt erosion and topsoil losses in these atypical Amazon soils.

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