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Characterization and Classification of Soils under Forest and Pasture in an Agroextractivist Project in Eastern Amazonia

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ABSTRACT: Knowledge of soils in the Amazon rainforest is becoming increasingly essential due to dynamics adopted by farmers that substitute forest for pastures, together with growing pressure from diverse segments of society towards adoption of sustainable production systems. The objective of this study was to characterize the soils along two toposequences, one under forest (F) and the other under pasture (P), and to verify how the change in land use influences soil attributes, evaluating their inclusion in the Brazilian Soil Classification System (SiBCS). The soils were sampled in pits located at the summit, backslope and footslope positions for morphological, chemical, physical, and clay mineralogy analysis. The results show that the soils are chemically poor and predominately kaolinitic. Sandy and loamy sand soils are in the surface horizons, with an increase in clay content with depth. The highest values of bulk density and lowest values of macroporosity were observed in the Bt horizons due to the change from a granular structure in the surface to an angular and subangular blocky structure in these horizons. The morphological properties observed in the field are strongly influenced by the annual soil water dynamics, the parent material, and the landscape, representing diagnostic characteristics that influenced classification of the soils, such as aquic with episaturation (*epirredóxico*), saprolitic, and gravelly. These diagnostic characteristics in the *Argissolo Amarelo* (Hapludults) are important morphological properties that have not been highlighted by the current edition of the SiBCS.

Keywords: *Argissolos*, Ultisols, southeast of Pará, soil classification, saprolitic character, aquic with episaturation (*epirredóxico*) character.

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INTRODUCTION

Rural colonization in Amazonia resulted in intense deforestation and, consequently, in an increase in soil degradation. In the Amazon biome, the use of pastures has been indicated as the major factor promoting extensive deforestation and causing serious losses to landscape dynamics (Ferraz et al., 2005; Grimaldi et al., 2014; Marichal et al., 2014).

Among the impacts caused by conversion of forests to cropland, we can cite changes in soil hydro-physical properties, such as reduction in total porosity and soil macroporosity, which affect the water infiltration rate and increase runoff, resulting in increased soil erosion (Zimmermann et al., 2010). The main factor in the change of vegetative cover from forest to pasture is modification of soil hydro-physical dynamics, as cited by Kairis et al. (2015). Braz et al. (2013) evaluated the chemical and physical changes caused to a *Latossolo Vermelho Distrófico* (Typic Hapludox) due to conversion from forest to pasture. The authors concluded that physical properties such as bulk density, porosity, and gravimetric moisture were different in forest soils compared to pasture soils, showing that land use change has important impacts on the soil.

The focus of other studies has been on changes caused by land use conversion on chemical properties (Mcgrath et al., 2001; Braz et al., 2013), soil C stocks and dynamics (Carvalho et al., 2010; Araújo et al., 2011; van Straaten et al., 2015), changes in the quantity and quality of shoot biomass (Fearnside and Barbosa, 1998; Lohbeck et al., 2015), emission of greenhouse gases through burning of forests and/or pastures (Fearnside, 2002; Fujisaki et al., 2015), soil biological activity (Silva et al., 2012; Rodrigues et al., 2013; Cram et al., 2015), reduction in ecosystem services (Grimaldi et al., 2014), and negative impacts on the invertebrate communities (Marichal et al., 2014).

In addition to contributing to evolution of knowledge regarding soil functioning in Amazonia, these studies assist in improving soil classification systems. The Brazilian Soil Classification System (SiBCS) has joined the properties of Brazilian soils and the research evolves information with the goal of encompassing all soils in the territory. The SiBCS (Santos et al., 2013c) includes different soil characteristics and properties that can be identified in the field or that can be inferred from soil science knowledge or correlated disciplines. This system is open, which means it allows new inclusions as new diagnostic characteristics emerge and are inserted in a specific soil class.

Given the dynamics adopted by farmers in substituting forest for pastures, together with increasing pressure of diverse segments of society in favor of adoption of sustainable production systems in Amazonia, is important to know the distribution of regional soil classes and understand their functioning so that alternative land use systems adapted to local conditions can be proposed for conservation purposes. Thus, the hypothesis of this work is that the substitution of native forest by pasture cause changes in the soil morphological, chemical and physical properties; and, consequently, in its functioning. The objective of this study is to characterize the soils and their relationship to position in the landscape along two toposequences, one under forest and the other under pasture, to understand the influence of land use changes on soil properties. We also seek to evaluate these properties to subsidize improved taxonomic framing of these soils in lower hierarchical levels of the Brazilian Soil Classification System.

MATERIALS AND METHODS

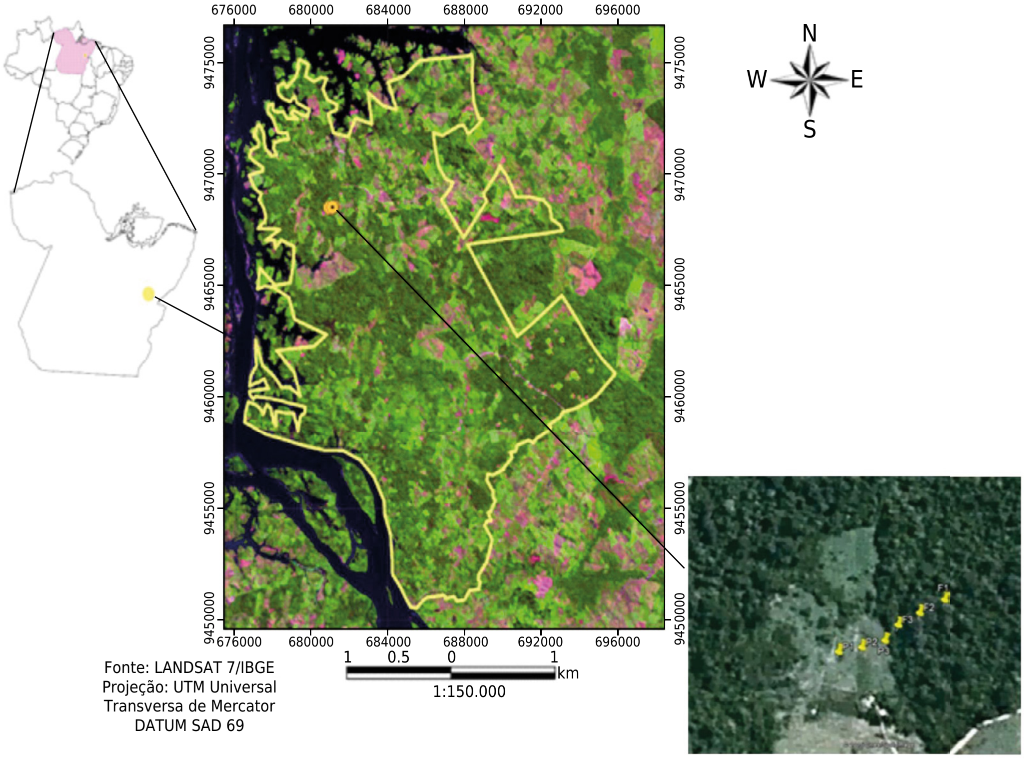
The study site is located in Maçaranduba II, part of the *Praialta Piranheira* Agroextractivist Settlement, municipality of Nova Ipixuna, Pará, Brazil, with geographic coordinates of 04° 56’ 16” S and 49° 04’ 37” W (Figure 1). The area is located inside the Peripheral

Depression of the southern Pará morphostructural unit, with planation surfaces, folded strips, metasedimentary cover, and dissection of hills due to erosion processes reactivated during the Holocene Epoch (Sampaio et al., 2004; Copserviços, 2009). According to Carneiro (2010), the settlement project is on the Bacajá geological domain, composed of rehydrated granulites of tonalitic and granulitic compostion, containing pyroxenes that give rise to soils rich in quartz, and small amounts of potassic feldspars affected by metamorphism with fragmented crystals, resulting in soils with fine textures (Vasquez and Rosa-Costa, 2008). The climate, according to the Köppen classification system, is Am, a very humid equatorial climate with annual rainfall of 2,000 mm and mean annual temperature of 26 °C (Inmet, 2015). Natural vegetation of the area is classified as Submontane Dense Ombrophilous Forest (Sampaio et al., 2004).

Two toposequences representative of the soils of the settlement project were studied. They were located in a watershed along the line of the highest slope, one across from the other. One of the toposequences was covered by primary forest (F) and the other by pasture (P), with a mean slope of 20 % for the forest toposequence and 14 % for the one under pasture. Part of the area under forest, approximately 20 ha, was converted to pasture using the traditional slash and burn system and posterior seeding of *Brachiaria brizantha* in 1996. During the first 10 years, the area was undergrazed (four to eigth head of cattle), and every 3 years the area was burned for pasture renovation and new seeding. Fire was last used in 2006; since then it remained fallow, with sporadic use of the pasture by neighboring cattle raisers.

At the footslope of both toposequences, a small creek separates both land uses. In the rainy season, this small watercourse undergoes fluctuations, increasing its flow rate, due to an increase in rainfall and also to the probable rise in the water table.

Three pits of approximately 1.65 m in depth were opened at the summit, backslope, and footslope of each of the toposequences, for soil characterization. Soil morphological



Fonte: LANDSAT 7/IBGE
Projeção: UTM Universal
Transversa de Mercator
DATUM SAD 69

Figure 1. Localization of the Agroextractivist *Praialta Piranheira* settlement project in the municipality of Nova Ipixuna, Pará, location of Maçaranduba II and the study site.

descriptions were made according to Santos et al. (2013a), and the bi-dimensional geometrical distribution of the soil horizons followed the structural analysis methodology proposed by Boulet et al. (1982). The bi-dimensional distribution of the horizons between the pits was detailed by taking undisturbed samples and disturbed samples using an auger in all soil horizons. The latter samples were air dried and sieved in a 2 mm mesh for chemical, physical, and mineralogical analyses.

Determinations of Al, Ca, Mg, K, available P, potential acidity, organic matter, and pH in water followed the methods proposed by Claessen (1997); sum of bases (SB), cation exchange capacity (T), base saturation (V), and aluminum saturation (m) were also calculated. The clay fraction minerals were separated according to Mehra and Jackson (1960) and identified by X ray diffractometry at 25 °C.

Particle size distribution was determined according to Gee and Or (2002). Gravel was separated and quantified manually; it was described and classified according to Santos et al. (2013c). Bulk density (Bd) was evaluated using the volumetric cylinder method, with sample sizes of 0.05 m height and 0.05 m diameter (Grossman and Reinsch, 2002). Particle density (Pd) was determined using the helium gas picnometer method (Flint and Flint, 2002). Total porosity (TP) and macro- and microporosity were determined using the tension table method (Claessen, 1997). The TP was determined by the saturated water content, microporosity by drainage with application of 6 kPa suction, and macroporosity by the difference between total porosity and microporosity. The soils were classified according to criteria established in the Brazilian Soil Classification System (Santos et al., 2013c) and Soil Taxonomy (Soil Survey Staff, 2014) (Table 1).

RESULTS AND DISCUSSION

Structural analysis was performed to understand soil distribution in the landscape in both toposequences and the vertical and horizontal differences among horizons. Local relief exhibits slopes that range from 3 to 20 %, and areas with low hills and flat summits. Figure 2 shows the distribution of the horizons along the toposequences under pasture and forest.

The A horizon has dark color (dark yellowish-brown to black), sandy texture, and predominantly granular structure. In the forest, the A horizon was shallower at the summit and backslope compared to the footslope of the toposequence, since the slope facilitates transport of part of the organic material downslope, as well as accumulation of plant residues in the lower parts of the landscape, transported by torrential rains, thus not permitting the development of deeper A horizons (Sanches et al., 2009). Under pasture, the formation of a deeper A horizon is caused by the presence of brachiaria and its root system morphology, which, after 7 years of fallow, contributes to development of a relatively deeper A horizon. This does not imply that the organic matter contents are higher in the surface horizons of the pasture compared to the forest surface horizons, because it is well known that although tropical forests have low fertility, the plants and biota have adapted mechanisms for acquisition of biomass and nutrient retention (Celentano et al., 2011).

The AB and BA horizons feature yellowish colors, and granular and subangular blocky structure (Table 1). The predominant texture is sandy clay loam, with the presence of gravel and coarse sand. Petroplinthite dominates the composition of the gravel, together with quartz. Horizons Bt1 and Bt2 featured a considerable increase in clay content, subangular blocky structure, and the presence of mottles, with colors varying from brownish-yellow to red. In horizons Bt3 and BC, the dominant structure is in the form of subangular blocks, and an increase in the abundance of mottles was observed, evidencing the presence of Fe redox processes.

Table 1. Morphological properties of the six profiles studied

Horizon	Depth	Moist color		Clay	Textural class(2)	Structure(3)	Gravel(4)
		Matrix	Mottles(1)				
	m			g kg^{-1}			%
F1 Summit: *Argissolo Amarelo Distrófico saprolítico, textura argilosa cascalhenta* (Typic Hapludults)							
A	0.00-0.06	10YR 4/4	10YR 5/6; po, pe, dif	150	Loamy sand	gr, me, mo, fo	
AB	0.06-0.17	10YR 5/6	-	330	Faa very gravelly	bs, gr, p, me, mo, fo	65
Bt1	0.17-0.44	10YR 5/8	5YR 5/8; co, g, dis	400	Sandy clay	bs, gr, p, mo	
Bt2	0.44-0.62	10YR 5/8	5YR 5/8; co, g, dis	500	Clay	bs, gr, p, me, mo	
			5YR 6/8; co, g, pro				
BC	0.62-0.99	7.5YR 5/6	10YR 6/8; ab, g, pro	600	Clay gravelly	bs, p, me, fo	40
Cr	0.99-1.63+	5YR 5/8	5YR 6/8; ab, g, pro	480	Clay	bs, p, mo, fo	
			10YR 7/8; ab, m, pro				
			2.5Y 7/8; ab, p, pro				
			10YR 6/8; ab, m, pro				
F2 Backslope: *Argissolo Amarelo Distrófico saprolítico, textura argilosa cascalhenta* (Typic Hapludults)							
A	0.00-0.06	10YR 5/6	-	130	Loamy sand	gr, p, me, fo	
AB	0.06-0.26	10YR 5/8	-	280	Faa very gravelly	bs, p, me, mo	70
Bt1	0.26-0.45	10YR 6/8	7.5YR 5/6; po, pe, dif	380	Sandy clay loam	bs, gr, p, mo	
Bt2	0.45-0.63	10YR 5/8	7.5YR 5/6; po, pe, dif	580	Clay	bs, gr, p, me, fo	
BC	0.63-0.90	2.5YR 5/6	2.5Y 6/8; ab, g, dis	450	Clay gravelly	bs, me, mo	35
Cr	0.90-1.65+	2.5YR 5/8	2.5YR 6/8; ab, m, pro	430	Clay with gravels	bs, me, g, fo	15
			2.5YR 8/3; ab, g, pro				
			2.5YR 4/4; ab, g, pro				
			10YR 6/8; ab, g, pro				
			2.5Y 6/8; co, m, pro				
F3 Footslope: *Argissolo Amarelo Distrófico saprolítico, textura argilosa cascalhenta* (Typic Hapludults)							
A	0.00-0.12	10YR 3/3	10YR 5/6; po, pe, dif	150	Loamy sand	gr, p, me, mo, fo	
AB	0.12-0.24	10YR 6/6	-	250	Faa very gravelly	bs, p, me, mo	80
Bt1	0.24-0.43	7.5YR 6/8	-	300	Sandy clay loam	bs, p, me, fo	
Bt2	0.43-0.58	7.5YR 6/6	5YR 5/8; po, pe, dif	400	Sandy clay	bs, me, mo	
Bt3	0.58-0.88	5YR 5/8	10YR 6/8; co, g, pro	380	Aa with gravel	bs, p, mo	20
			2.5Y 6/8; po, pe, pro				
BC*^{Fr}	0.88-1.27	5YR 5/8	10YR 7/8; co, g, pro	250	Faa with gravel	bs, p, me, mo, fo	20
Cr	1.27-1.60+	2.5YR 5/8	2.5YR 4/6; po, p, pro	230	Sandy clay loam	bs, g, fo	
			10YR 7/8; ab, gr, dis				
			2.5Y 8/4; po, p, pro				
			7.5YR 5/6; ab, gr, dis				
P1 Summit: *Argissolo Amarelo Distrófico saprolítico, textura argilosa cascalhenta* (Typic Hapludults)							
A	0.00-0.05	10YR 3/3	-	100	Loamy sand	gr, p, mo	
AB	0.05-0.13	2.5Y 4/4	5YR 4/6; po, p, dif	170	Far very gravelly	bs, gr, me, mo	80
			2.5Y 5/6; po, p, dif				
Bt1	0.13-0.67	10YR 6/8	10YR 3/3; po, p, dif	370	Sandy clay	bs, pr, p, fr, mo	
			2.5Y 4/4; po, p, dif				
Bt2	0.67-0.93	7.5YR 6/8	-	500	Clay with gravel	bs, pr, p, mo	30
BC	0.93-1.21	7.5YR 6/8	5YR 5/8; ab, g, pro	570	Clay gravelly	bs, pr, p, me, mo	50
Cr	1.21-1.80+	5YR 5/8	10YR 6/8; ab, m, pro	500	Clay	ba, p, me, fo	
			2.5Y 7/8; ab, m, pro				
P2 Backslope: *Argissolo Amarelo Distrófico saprolítico, textura argilosa cascalhenta* (Typic Hapludults)							
A	0.00-0.09	10YR 3/2	-	200	Loamy sand	gr, p, me, mo	
BA	0.09-0.18	10YR 5/8	7.5YR 5/8; po, p, dif	300	Faa very gravelly	ba, gr, p, fo	75
			5Y 4/2; po, p, dif				

Continue...

Continuation...

Bt	0.18-0.44	7.5YR 6/8	10R 4/8; po, p, dif	400	Clay loam	ba, p, me, mo	
BC	0.44-0.85	7.5YR 6/8	10R 5/6; co, p, dis	420	Clay gravelly	ba, pr, p, me, mo, fo	45
			10R 5/8; co, p, dis				
			10R 4/4; co, m, pro				
			10YR 7/8; co, m, dis				
Cr	0.85-1.60+	10R 3/4	10R 4/6; co, g, dis	270	Clay loam	ba, pr, p, me, mo, fo	
			10R 4/8; co, m, pro				
			10R 6/8; co, p, dis				
			10R 7/6; po, p, dis				
			7.5YR 6/8; co, m, pro				
			2.5YR 6/8; po, p, dis				
			2.5YR 7/8; po, p, dis				
P3 Footslope: *Argissolo Amarelo Distrófico epirredóxico argilosa, textura argilosa cascalhenta* (Typic Hapludults)							
A	0.00-0.09	10YR 2/1	-	70	Loamy sand	gr, p, fr, mo	
AB**^{Re}	0.09-0.15	10YR 6/8	2.5Y 8/8; co, p, pro	120	Far very gravelly	bs, p, me, mo	80
			7.5YR 7/8; po, p, dis				
			10YR 3/1; co, p, dis				
			10YR 5/6; co, p, dis				
BA	0.15-0.37	2.5Y 7/6	10YR 6/8; co, p, dif	250	Sandy clay loam	bs, p, me, mo	30
Bt1	0.37-0.76	2.5Y 7/6	5YR 5/6; po, p, dis	350	Sandy clay	ba, me, mo	
			7.5 YR 6/6; co, m, dif				
Bt2	0.76-1.10	5YR 5/8	2.5YR 5/8; co, m, dif	480	Clay gravelly	ba, me, fo	40
			10YR 7/8; co, m, dif				
BC	1.10-1.33+	10R 4/8	10YR 7/8; co, m, pro	480	Clay	ba, me, fo	

(1) Mottles: po: few; co: common; ab: abundant; pe: small; m: medium; g: large; dif: diffuse; dis: distinct; pro: proeminent; F: forest; P: pasture. (2) Faa: sandy clay loam; Aa: sandy clay; Far: loamy sand. (3) bs: subangular block; ba: angular block; gr: granular; pr: prismatic; p: small; me: medium; g: large; fr: weak; mo: moderate; fo: strong. (4) Nodules and mineral concretion: mostly quartz and petroplinthite. *^{Fr}: fragments. **^{Re}: redox horizon.

The C horizon is made up of alteration or saprolitic material, with an increase in the coarse sand fraction and without much gravel. The material is a continuous mass that breaks up into angular and subangular blocks.

At the footslope of the pasture toposequence and below the A horizon, a non-continuous horizon appears, in this case named Re (redoxic). This horizon features evidences of redox processes and mottles of greyish colors, related to restricted drainage, conditioned by proximity to the water table and its position in the landscape. In the forest, also in the lower part of the toposequence, below the Bt horizon, a moist horizon appears, with yellowish colors and low clay content; it has high abundance of coarse sand and considerable influence of the water table, with the presence of parent material fragments larger than those found in other horizons of both toposequences, with stones and boulders. In this case, the horizon was designated as Fr (fragments).

On both toposequences, the A and AB horizons have granular and crumb structures with a moderate grade, favored by the presence of organic matter and biological activity. Due to the contribution of this type of structure under forest and pasture, macroporosity was important down to the depth of 0.25 m (Santos et al., 2010) (Tables 1 and 3). In the subsurface horizons, beginning in the Bt horizon, the structure grade varied from moderate to strong, the structure type alternated from medium subangular blocks to medium and large angular blocks, and an increase in clay content was observed. These properties found in the subsurface Bt horizons led to a reduction in soil hydraulic conductivity, leading to formation of a perched water table, which is evidenced by the presence of hydromorphic features such as mottles (Embrapa, 2006; Juhász et al., 2006). The blocky structure of the subsurface horizons can occur as a consequence of the action of alternate wetting and drying cycles (Santos et al., 2010).

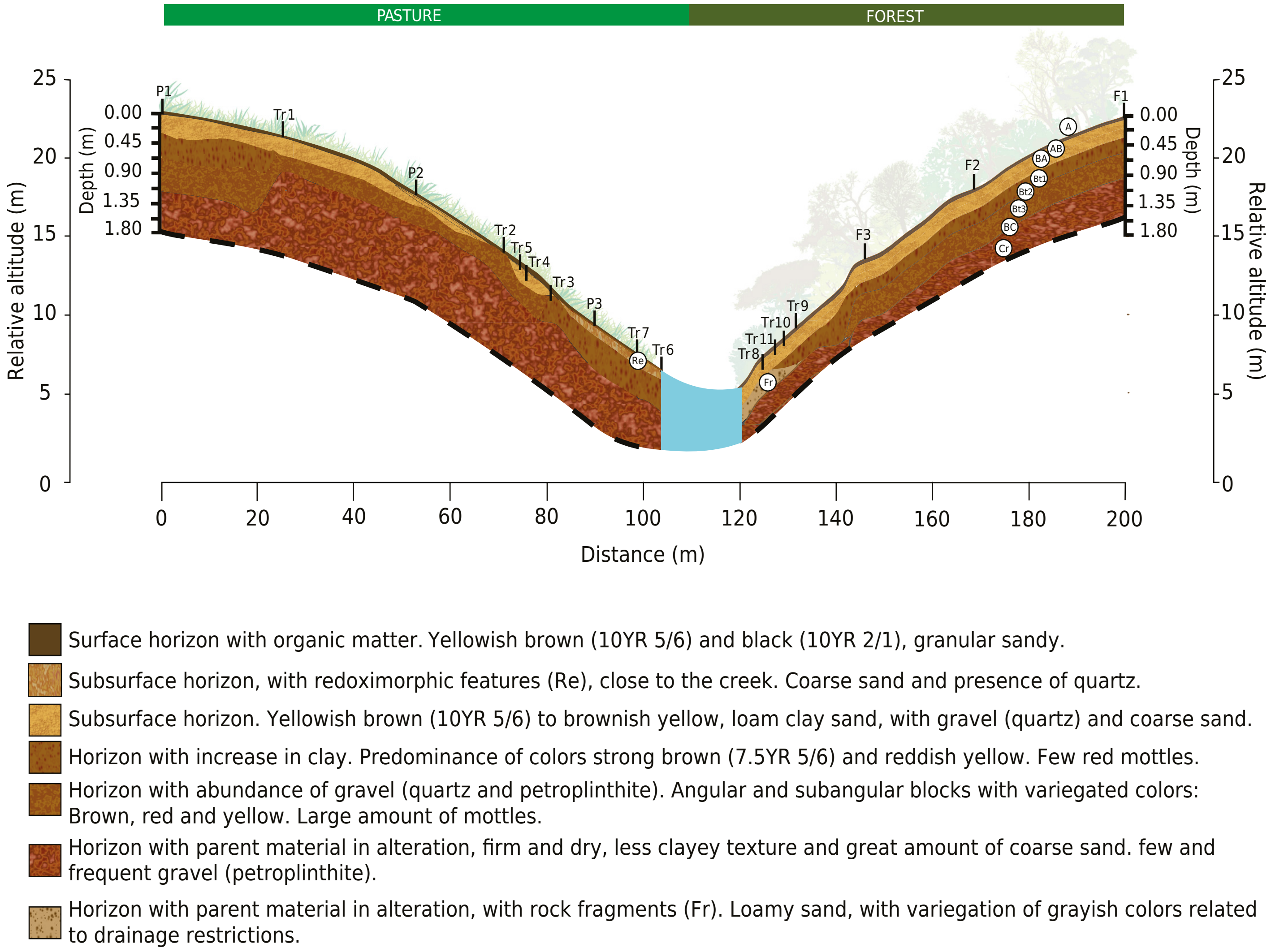


Figure 2. Structural analysis of the toposequence. P: profile under pasture; F: profile under forest; Tr: auger hole.

The sequence of the soil horizons in profile F1, situated at the summit of the toposequence under forest, was A-AB-Bt1-Bt2-BC-C. This soil was characterized as deep, with an increase in clay content with depth. In addition, hue 10YR was observed in the surface horizons and an increase in chrome in the deeper horizons. Profile F2, situated on the backslope, featured a horizon sequence similar to the previous profile, A-AB-Bt1-Bt2-BC-C. This profile has a 7.5YR hue in the deeper horizons, with brownish colors dominating from the depth of 0.5 m, and in the BC and C horizons, reddish and yellowish colors dominate (hue 2.5YR). In profile F3, at the footslope, the sequence of horizons was A-AB-Bt1-Bt2-Bt3-BC-C, featuring higher mottling when compared to the other profiles. Hues varied between brownish and red yellow (10YR, 7.5YR, and 5YR).

The color of the soils was influenced by water dynamics, probably due to the fluctuation of the water table in the lower parts of the landscape and to the great volumes of rain that influence the entire profile, especially the surface horizons. In a similar study, Campos et al. (2012) also found that soil color varied from red, in the summit positions, to yellow in the backslope, and red yellow in the footslope and low summits. These authors agree that color variation is conditioned by the water flux downhill, via runoff and subsurface lateral flux, and, therefore, influenced by position in the landscape, as well as by its strong relationship with parent material.

In profile P1, at the summit under pasture, the sequence of horizons was A-AB-Bt1-Bt2-BC-C. In this profile, the dark brown color (10YR) was observed in the surface and subsurface horizons. From the surface to 0.10 m depth, olive brown and yellowish red (2.5Y and 5YR) colors appear in the form of mottles. From 0.67 m, the reddish yellow (7.5YR) and yellowish red (5YR) colors predominated. In profile 2, situated on the backslope, the sequence of horizons was A-BA-Bt-BC-C, with a grayish brown color (10YR) in the surface transitioning to yellow red in the subsurface, until the predominance of red (10R) in the C horizon. In this profile, the absence of the AB horizon could be due to the position this profile occupies in the landscape. The presence of mottles increases in the Bt horizon. In profile P3, situated at the footslope, the sequence of horizons is A-AB-BA-Bt1-Bt2-BC, with predominance of dark colors (10YR 2/1) in the surface layers. Yellow (2.5Y) and red (2.5YR and 10R) mottles are observed from 0.15 m down to the BC horizon (1.33 m).

Both in forest and in pasture, even with the presence of mottling that conferred various colors to these soils, hues 7.5YR or yellower were dominant down to the depth of 1 m of the B horizon (including the BA horizon). Thus, according to the SiBCS (Santos et al., 2013c), the soils of both toposequences fall under the suborder *Amarelos*.

The redox characteristic appeared in zones closer to the soil surface, in small scale, and can be related to temporary saturation of the surface horizons, probably due to the formation of a perched water table at the top of the Bt horizon, as explained above. The presence of this feature in deeper layers of the soil can be explained by the fluctuation of the water table and the influence of the rainfall period throughout the profile (Figure 2). High soil moisture contents in the soil profile for long periods of the year favor redox processes, which contribute to the solubilization and precipitation of Fe, as was evidenced by the redoximorphic features in the form of mottles, plinthite, and petroplinthite observed in the soils studied (Benedetti et al., 2011; Campos et al., 2012; Garcia et al., 2013; Santos et al., 2013b).

The results of chemical analysis show low values of pH, high exchangeable Al contents, and limited availability of nutrients in these soils (Table 2). In all profiles, for both land uses, the pH in water ranged from 3.9 to 5.0. The lowest values were found in the backslope of the forest (F2), while the highest values were found in the summit profile of the pasture (P1), with a maximum value of 5.5 in the soil surface. Based on these pH values, the profiles under forest can be classified as extremely to strongly acid (Santos et al., 2013c), whereas, under pasture, the soils are less acid, probably due to soil management, as the use of fire for forest removal is very common in this region, and the ashes deposited on the soil elevate the value of pH, which can remain high for decades, as shown by Mcgrath et al. (2001), Quesada et al. (2010), and Araújo et al. (2011).

The potential and exchangeable acidity in both land uses exhibited moderate and high values in all profiles and depths, as observed by Freitas et al. (2013), for Amazonian soils under forest, pasture, and other land uses. Under forest, the potential acidity values ranged from 1.2 to 2.6 $\text{cmol}_c\ \text{kg}^{-1}$; under pasture, from 1.7 to 2.1 $\text{cmol}_c\ \text{kg}^{-1}$; and in the footslope profile, the values were lower and ranged from 1.1 to 1.8 $\text{cmol}_c\ \text{kg}^{-1}$. The values of exchangeable acidity were more constant under forest with moderate levels (ranging from 0.5 to 0.9 $\text{cmol}_c\ \text{kg}^{-1}$) than under pasture, where values considered high were observed, mainly in the diagnostic horizons of the P1 and P2 profiles. P3 also had low values of Al^{3+} compared to the rest of the profiles. The values of aluminum saturation (m) found under forest were moderate to very high; lower values were found in the pasture, mainly in the surface horizons of the three profiles. In the deeper horizons of the pasture, the values increased to high and very high (Lopes e Guidolin, 1989).

The K, P, Ca, and Mg contents were considered low in all profiles along the toposequences (Table 2). These results confirm the intense leaching of bases in these profiles due to the intense and frequent rainfalls in the Amazon forest (Freitas et al., 2013). Similar results were found by Schroth et al. (2000), who analyzed nutrient concentrations in perennial crops, fallow areas, and forest in Central America.

Table 2. Chemical properties of the six profiles studied

Horizon	Depth	pH		Al^{3+}	H+Al	K^+	Ca^{2+}	Mg^{2+}	SB	MO	P	V	m
		H_2O	KCl										
	m			$cmol_c\ kg^{-1}$						dag kg^{-1}	mg dm^{-3}	%	
F1 Summit: *Argissolo Amarelo Distrófico saprolítico, textura argilosa cascalhenta* (Typic Hapludults)													
A	0.00-0.06	3.9	3.6	0.88	4.36	0.17	3.12	5.81	10.65	32.51	8.59	19.63	45.21
AB	0.06-0.17	3.9	3.9	0.91	2.88	0.13	0.04	1.48	2.85	11.54	2.23	8.99	76.21
Bt1	0.17-0.44	4.4	4.0	0.88	2.38	0.08	0.00	1.60	2.41	10.96	1.32	9.21	78.50
Bt2	0.44-0.62	4.7	4.1	0.64	2.18	0.08	0.00	3.37	4.16	12.13	1.14	16.03	60.62
BC	0.62-0.99	5.0	4.2	0.69	2.26	0.07	2.00	4.18	6.93	4.87	1.05	23.46	49.93
Cr	0.99-1.63+	4.7	4.1	0.81	1.98	0.11	0.11	2.95	4.15	3.62	0.95	17.34	66.11
F2 Backslope: *Argissolo Amarelo Distrófico saprolítico, textura argilosa cascalhenta* (Typic Hapludults)													
A	0.00-0.06	3.9	3.8	0.60	2.46	0.09	1.15	1.22	3.26	13.02	5.50	11.71	64.79
AB	0.06-0.26	4.1	3.9	0.86	2.24	0.04	0.28	0.73	1.37	9.53	2.41	5.77	86.23
Bt1	0.26-0.45	4.3	4.0	0.84	2.16	0.04	0.37	1.24	1.97	8.97	1.50	8.37	81.01
Bt2	0.45-0.63	4.7	4.1	0.82	2.24	0.02	0.04	2.78	3.04	6.37	1.14	11.96	72.88
BC	0.63-0.90	4.8	4.1	0.91	1.96	0.01	0.03	2.00	2.15	6.68	1.23	9.88	80.94
Cr	0.90-1.65+	4.8	4.1	1.19	2.16	0.01	0.00	1.19	1.31	1.43	1.14	5.74	90.10
F3 Footslope: *Argissolo Amarelo Distrófico saprolítico, textura argilosa cascalhenta* (Typic Hapludults)													
A	0.00-0.12	3.9	3.7	0.88	2.68	0.14	1.74	2.17	5.30	17.28	9.95	16.52	56.94
AB	0.12-0.24	4.2	4.0	0.91	2.32	0.12	0.44	2.09	3.71	12.21	4.68	13.79	65.30
Bt1	0.24-0.43	4.4	4.0	0.70	1.72	0.10	0.28	3.69	4.99	9.40	2.23	22.49	56.22
Bt2	0.43-0.58	4.6	4.1	0.70	1.90	0.10	0.26	3.23	4.47	7.67	1.68	19.03	60.41
Bt3	0.58-0.88	4.8	4.3	0.64	1.40	0.09	0.14	1.59	2.69	5.10	1.23	16.11	68.34
BC*	0.88-1.27	5.0	4.3	0.68	0.98	0.10	0.00	0.63	1.61	4.23	1.23	14.08	73.66
Cr	1.27-1.60+	4.9	4.2	0.58	1.20	0.07	0.00	0.35	1.00	3.29	0.95	7.73	86.80
P1 Summit: *Argissolo Amarelo Distrófico saprolítico, textura argilosa cascalhenta* (Typic Hapludults)													
A	0.00-0.05	5.5	4.6	0.15	1.78	0.25	8.07	6.47	17.07	25.40	16.86	48.96	8.12
AB	0.05-0.13	4.9	4.3	0.22	2.92	0.35	5.09	4.14	12.71	18.30	4.50	30.33	14.81
Bt1	0.13-0.67	4.2	3.9	1.35	3.04	0.08	0.87	0.36	2.07	9.73	2.50	6.37	86.68
Bt2	0.67-0.93	4.2	3.9	1.10	3.24	0.10	0.44	0.16	1.64	8.05	2.41	4.80	87.10
BC	0.93-1.21	4.6	4.1	1.15	2.24	0.07	0.37	0.16	1.18	7.29	1.32	5.01	90.73
Cr	1.21-1.80+	4.7	4.1	0.44	2.26	0.12	0.15	0.37	1.71	5.05	1.95	7.05	87.39
P2 Backslope: *Argissolo Amarelo Distrófico saprolítico, textura argilosa cascalhenta* (Typic Hapludults)													
A	0.00-0.09	4.6	4.6	0.73	2.18	0.08	4.98	1.95	7.71	17.33	5.23	26.12	36.32
BA	0.09-0.18	4.5	4.3	1.12	2.28	0.04	4.00	0.93	5.37	14.40	2.14	19.07	57.6
Bt	0.18-0.44	4.4	3.9	1.28	2.70	0.02	2.21	1.01	3.45	11.31	4.32	11.32	76.53
BC	0.44-0.85	4.8	3.9	1.18	2.36	0.02	1.54	1.11	2.87	8.05	2.14	10.84	81.69
Cr	0.85-1.60+	4.6	4.1	0.35	1.98	0.03	0.39	0.58	1.27	2.19	0.95	6.04	90.34
P3 Footslope: *Argissolo Amarelo Distrófico epirredóxico argilosa, textura argilosa cascalhenta* (Typic Hapludults)													
A	0.00-0.09	4.8	4.1	0.29	1.84	0.09	8.21	2.31	11.43	16.41	7.77	38.32	23.42
AB**	0.09-0.15	4.8	4.6	0.22	1.78	0.06	6.36	0.76	7.72	13.53	5.68	30.26	27.35
BA	0.15-0.37	4.8	4.3	0.22	1.78	0.06	6.36	0.76	8.33	13.53	5.68	42.21	27.28
Bt1	0.37-0.76	4.6	3.9	0.30	1.14	0.03	7.37	0.65	6.43	11.34	7.32	31.77	20.91
Bt2	0.76-1.10	5.0	3.9	0.65	1.38	0.02	4.89	1.30	4.71	6.57	4.59	20.03	31.84
BC	1.10-1.33+	5.1	4.1	0.85	1.88	0.14	0.38	2.97	3.71	1.63	1.14	15.38	58.02

pH in water and 1 mol L^{-1} KCl; H+Al: potential acidity; MO: organic matter; SB: sum of bases; V: base saturation; m: aluminum saturation.

The available P in both land uses had higher values in the surface horizons, decreasing along the profile due to the low mobility of soil P and to the low contribution of ash deposition due to burning, in the case of pasture (Freitas et al., 2013). T, SB, and V values were also considered low in both toposequences (Table 2). These properties were higher in the first 0.2 m of the soil. In general, organic matter contents were concentrated in the surface horizons in both land uses, decreasing with depth. These contents ranged from 32.51 to 1.43 g kg^{-1} under forest and from 25.40 to 1.63 g kg^{-1} under pasture. The higher content of organic C in the surface horizons is related to the higher material input and cycling in this site. In tropical environments, due to high temperatures and mineralization rates of organic matter, the stability of this material is low. Generally, the organic matter contents are lower than 30 g kg^{-1} in the surface horizons in most of the Amazon soils (Quesada et al., 2010; Garcia et al., 2013).

The six profiles had V lower than 50 % (Table 2), with low pH in all soil horizons. This characterizes the soils as dystrophic, an important characteristic that defines the third SiBCS categorical level of the soils studied (Santos et al., 2013c).

The mineralogical composition of the clay fraction did not show great variation of minerals along the toposequences. Analysis revealed the dominance of kaolinite, as well as small quantities of gibsite, illite, and quartz (Figure 3). This result corroborates studies that evidence kaolinite as the main mineral of the clay fraction of Amazonian soils (Corrêa et al., 2008; Benedetti et al., 2011).

The particle size distribution of the soil horizons up to 0.20 m had clay contents from 120 to 300 g kg^{-1} in all profiles and were characterized as loamy sand and loamy clay sand (Santos et al., 2013c). From 0.6 m, profiles F1, F2, P1, P2, and P3 are clayey, with clay contents superior to 460 g kg^{-1}, featuring an abrupt textural change. This change

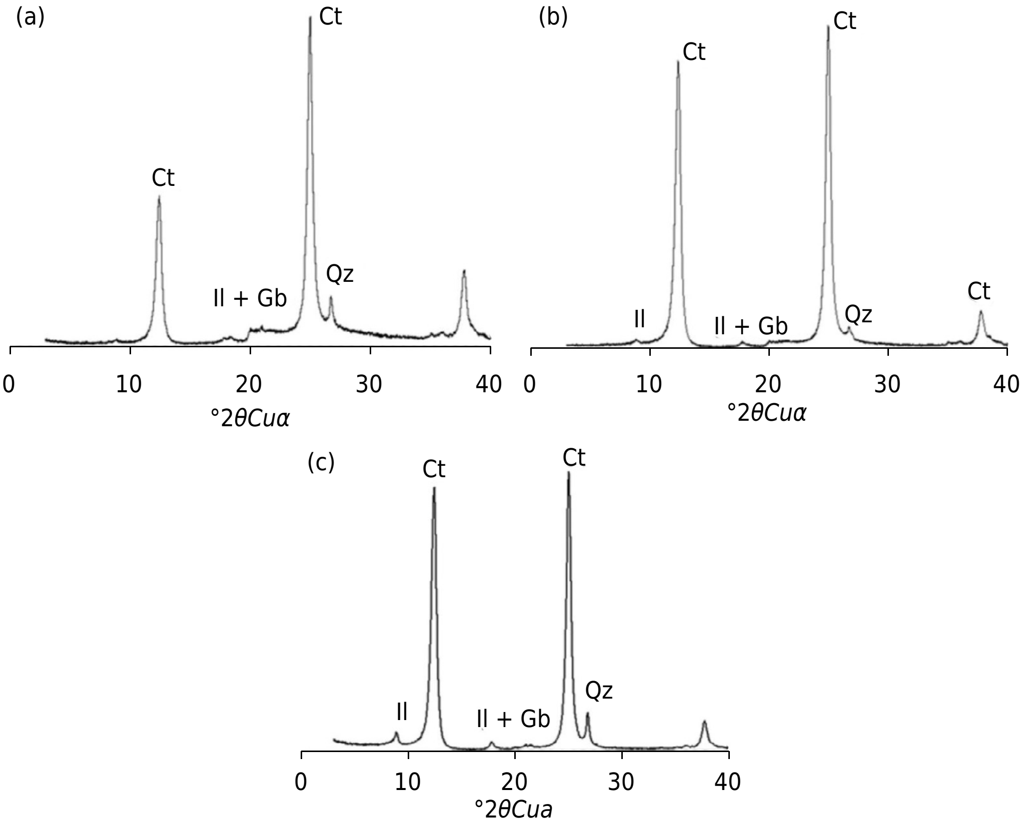


Figure 3. Clay fraction diffractograms of the toposequence studied. Examples of some profiles and depths analyzed. (A: F1 0.06-0.17 m, B: F2 0.45-0.63 m, C: P3 0.15-0.37 m). Ct: Kaolinite; Il: Illite; Gb: Gibbsite; Qz: Quartz.

occurs in forest between the A and AB horizons, while under pasture, between the AB and B horizons (including Bt1 and BA). Horizon C, in profiles F3 and P2, contains less clay (250 g kg^{-1}, 270 g kg^{-1}) (Table 1). Soils of both land uses developed a textural B horizon, with higher clay contents than the A and C horizons, and an increase in the clay content, with a B/A textural ratio above 1.80, made up of low activity clays and low base saturation, which classifies them as *Argissolos* in the Brazilian Soil Classification System (Santos et al., 2013c) or Ultisols in Soil Taxonomy (Soil Survey Staff, 2014).

From the depth of 1.00 m, the horizons have gravel size fragments, with characteristics similar to the C horizon material, and changes in soil texture. These properties contribute to classification of five profiles in this study in the 4th categorical level (subgroups) as saprolitic. The criteria established by Santos et al. (2013c) assume that the saprolitic character occurs in soils with Cr (soft) in the first 1.0 m from the soil surface and without lithic contact in the first 1.5 m from the soil surface. Nevertheless, this diagnostic characteristic only exists for *Argissolos Vermelhos Eutróficos* and *Eutroférricos* (Typic Rhodudalfs); thus, we suggest that it should also be applied to the suborder of the *Argissolos Amarelos Distróficos* (Typic Hapludults).

Gravel appears with more frequency from the depth of 0.4 m, where generally the more clayey horizons of the toposequences begin. Horizon Bt of P3 had the most gravel. Gravels are formed as residues of the parent material, from quartz and largely petroplinthite, but not in sufficient quantities to satisfy the requirements of the plinthic character, according to Santos et al. (2013c). This aided in identification of the 5th categorical level of classification of these soils as poorly gravelly and gravelly (Santos et al., 2013c). The poorly gravelly and gravelly classes are likewise not included in the *Argissolos Amarelos* (Ultisols); thus, we also suggest inclusion of this diagnostic characteristics in the 5th categorical level for these soils.

The Bd values for the surface horizons ranged from 1.26 to 1.58 Mg m^{-3} in the toposequence under forest, while for pasture the values ranged from 1.27 to 1.63 Mg m^{-3} (Table 3). At the surface, the incidence of low specific weight organic matter contributed to reduce soil bulk density, as well as increase macroporosity and facilitate formation of a granular and crumby structure (Bilibio et al., 2010), promoting better aeration and other gas exchanges, as well as water flow.

The soil horizons with an increase in clay content, Bt, had variations in Bd from 1.41 to 1.53 Mg m^{-3} under forest, and from 1.47 to 1.69 Mg m^{-3} under pasture. The Bd of the deepest horizon, C, made up of alteration materials, ranged from 1.40 to 1.44 Mg m^{-3} under forest, while under pasture it ranged from 1.42 to 1.68 Mg m^{-3}. The higher values of Bd in the surface horizons of the pasture primarily occurred due to the presence of higher contents of sand, which naturally has Pd than clay (Dias Junior and Estanislau, 1999). Secondly, the change in land use, from forest to pasture, together with the wetting and drying cycles, probably contributed to such values (Araújo et al., 2004; Figueiredo et al., 2009). In general, the highest values of Bd of the toposequences occurred in the Bt horizons. This is correlated with the structural change that occurs between the granular structure in the surface horizons and the angular and subangular blocky structure of the subsurface horizons, as well as the soil textural change from sandy, with higher macroporosity, to clayey, with higher microporosity. Gravel, present mainly in depth, also influences these values of Bd, and these gravels are found in the horizons with the highest clay contents due to drainage restriction (Figueiredo et al., 2009), the occurrence of petroplinthite, and altered parent material.

Pore distribution in the pasture revealed a reduction in macropores and micropores compared to the forest, regardless of the position in the landscape (Table 3). The soil macroporosity results were adequate (above 0.10 m^3 m^{-3}) for good quality soils in the surface horizons under forest (F1, F2, F3) and pasture (P1, P2, P3). In contrast, the soil macroporosity results for the deeper Bt and C horizons of profiles F1, F2, and F3

Table 3. Soil particle density (Pd) and bulk density (Bd), macro- and microporosity, and total porosity (TP) of the six profiles studied

Horizon	Depth	Pd	Bd	Macro	Micro	TP
	m	Mg m^{-3}			m^3 m^{-3}	
F1 Summit: *Argissolo Amarelo Distrófico saprolítico, textura argilosa cascalhenta* (Typic Hapludults)						
A	0.00-0.06	2.58	1.26	0.32	0.19	0.51
AB	0.06-0.17	2.60	1.58	0.14	0.12	0.26
Bt1	0.17-0.44	2.61	1.54	0.21	0.28	0.49
Bt2	0.44-0.62	2.60	1.52	0.15	0.23	0.39
BC	0.62-0.99	2.61	1.47	0.11	0.37	0.48
Cr	0.99-1.63+	2.64	1.41	0.11	0.17	0.28
F2 Backslope: *Argissolo Amarelo Distrófico saprolítico, textura argilosa cascalhenta* (Typic Hapludults)						
A	0.00-0.06	2.60	1.47	0.26	0.19	0.45
AB	0.06-0.26	2.61	1.52	0.15	0.27	0.42
Bt1	0.26-0.45	2.61	1.50	0.18	0.22	0.40
Bt2	0.45-0.63	2.61	1.41	0.18	0.32	0.50
BC	0.63-0.90	2.62	1.43	0.10	0.15	0.25
Cr	0.90-1.65+	2.62	1.40	0.10	0.17	0.27
F3 Footslope: *Argissolo Amarelo Distrófico saprolítico, textura argilosa cascalhenta* (Typic Hapludults)						
A	0.00-0.12	2.60	1.28	0.23	0.23	0.46
AB	0.12-0.24	2.61	1.52	0.19	0.12	0.31
Bt1	0.24-0.43	2.61	1.39	0.15	0.09	0.24
Bt2	0.43-0.58	2.61	1.43	0.13	0.14	0.27
Bt3	0.58-0.88	2.62	1.37	0.11	0.18	0.29
BC	0.88-1.27	2.61	1.40	0.07	0.22	0.29
Cr	1.27-1.60+	2.63	1.44	0.07	0.25	0.32
P1 Summit: *Argissolo Amarelo Distrófico saprolítico, textura argilosa cascalhenta* (Typic Hapludults)						
A	0.00-0.05	2.58	1.27	0.24	0.28	0.52
AB	0.05-0.13	2.60	1.63	0.27	0.15	0.42
Bt1	0.13-0.67	2.60	1.52	0.31	0.12	0.43
Bt2	0.67-0.93	2.61	1.41	0.36	0.12	0.48
BC	0.93-1.21	2.61	1.46	0.20	0.11	0.31
Cr	1.21-1.80+	2.61	1.46	0.20	0.11	0.31
P2 Backslope: *Argissolo Amarelo Distrófico saprolítico, textura argilosa cascalhenta* (Typic Hapludults)						
A	0.00-0.09	2.60	1.52	0.16	0.29	0.45
BA	0.09-0.18	2.61	1.59	0.15	0.30	0.45
Bt	0.18-0.44	2.61	1.53	0.15	0.32	0.47
BC	0.44-0.85	2.64	1.58	0.12	0.18	0.30
Cr	0.85-1.60+	2.65	1.68	0.08	0.13	0.21
P3 Footslope: *Argissolo Amarelo Distrófico epirredóxico argilosa, textura argilosa cascalhenta* (Typic Hapludults)						
A	0.00-0.09	2.61	1.48	0.23	0.24	0.47
AB	0.09-0.15	2.62	1.51	0.19	0.20	0.39
BA	0.15-0.37	2.62	1.67	0.14	0.20	0.34
Bt1	0.37-0.76	2.61	1.71	0.16	0.13	0.29
Bt2	0.76-1.10	2.63	1.47	0.08	0.23	0.31
BC	1.10-1.33+	2.67	1.42	0.09	0.26	0.35

under forest and profiles P1, P2, and P3 under pasture had values below the minimum necessary (0.10 $m^3 m^{-3}$) to ensure good aeration and oxygen diffusion for the root system (Xu et al., 1992).

The decrease in soil porosity with depth was also observed by Desjardins et al. (2004). According to these authors, this decrease may be due to textural and structural modifications along the profile. In the soils of this study, the increase in clay with depth corroborates such observations. Soil bulk density, which increases in depth, and the angular and subangular blocks found in the subsurface horizons contribute to the lower number of pores in the clayey horizons; whereas in the surface horizons with sandier textures, small and medium granular structure, and lower soil bulk density, the porosity was higher (Table 1 and 3).

The soil microporosity results observed in the forest and pasture toposequences had lower minimum and maximum values in the surface horizons from 0.17 to 0.27 $m^3 m^{-3}$. These values increased in depth in the clayey Bt horizons from 0.19 to 0.37 $m^3 m^{-3}$, and in the alteration horizons (C), with values from 0.23 to 0.37 $m^3 m^{-3}$ (Table 3).

In the specific case of P3, the high Bd and presence of micropores in the Bt1, Bt2, and C horizons probably contributed to the expressive modification in soil water dynamics, favoring the process of retention, which, together with fluctuation in the water table, favors the emergence of redox features (mottles and plinthite), which leads to the variation in colors described above. Based on these observations and on the discussions raised in this study, we suggest the inclusion, also in the 4th categorical level, of the aquic with episaturation (*epirredóxico*) character in the *Argissolos Amarelos* (Typic Hapludults). Currently, this characteristic is only admitted in the *Argissolos Vermelhos* (Typic Rhodudalf) (Santos et al., 2013c). In the previous editions of the SiBCS (Embrapa, 1999; 2006) the epiaquic character was admitted in the 4th categorical level. The current edition (Santos et al., 2013c) includes the epiaquic character in the redox character, expanding its limits to situations with the presence of redoximorphic features, both in surface and subsurface horizons. In this sense, based on the SiBCS (Santos et al., 2013c) and on field and laboratory observations, the profiles were classified as: *Argissolo Amarelo Distrófico saprolítico, textura cascalhenta* (PAd) for F1, F2, F3, P1, and P2; and *Argissolo Amarelo Distrófico epirredóxico, textura cascalhenta* (PAd) for P3. The suggestions for inclusion of new classes in the 4th categorical level are relevant and should serve as a stimulus for new studies for development of the *Argissolo Amarelo* (Hapludults) class.

CONCLUSIONS

Soil response under pasture underwent modifications due to changes in the vegetative cover. The higher values of pH, bulk density, and microporosity and greater presence of plinthite and mottles show a possible direct relationship to change in land use.

The chemical and mineralogical properties characterize the soils studied as poor and predominantely kaolinitic. Morphologically, the differences found in the profiles are related to the characteristics of the *Argissolos* (Ultisols): lower clay content and granular structure in the surface horizons, with higher macroporosity and, consequently, lower bulk density; and higher clay content and blocky structure in the subsurface horizons, with higher microporosity.

The soils along the toposequences are classified up to the 3rd categorical level of the current edition of the SiBCS. We suggest the inclusion of the aquic with episaturation (*epirredóxico*) and saprolitic diagnostic characters in the 4th categorical level for the *Argissolos Amarelos Distróficos* (Typic Hapludults), and the gravelly character in the 5th categorical level.

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