GENESIS AND CLASSIFICATION OF SOILS OVER FOREST AND PASTURE IN A TOPOSEQUENCE, IN SOUTHERN AMAZONIA

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Abstract. The state of Rondônia has several soil classes, many of which have been subjected to conversion from forest to pasture by the use of fire, causing irreversible damage. Thus, studies are needed to assess changes in soil attributes, as a way to provide information that minimizes the impacts generated. Thus, the objective was to characterize, classify and evaluate the fragility of soils when used as pastures in a toposequence in the district of União Bandeirantes, Porto Velho, Rondônia, Brazil. In the field, a toposequence was selected, where the profiles corresponding to each environment were selected based on the relief position, vegetation patterns (forest and pasture), pedological characteristics and parent material. In each environment, trenches were opened, which were morphologically characterized and samples were collected for physical-chemical analysis of the soil in the laboratory. The soils were classified according to the criteria established by the Brazilian Soil Classification System and by the World Reference Base for Soil Resources. Additionally, multivariate statistics were performed. In profiles P1 to P5, a monochromatic pattern was observed between the horizons. Soil profiles showed textural classes ranging from clayey loam to very clayey. Along the toposequence, two orders of soils, Latossolos and Plintossolos, were observed, which showed differences in the lower categorical levels. In the superficial horizons, modifications were observed in the attributes of granulometry, soil density, exchangeable bases and acidity components. By the multivariate analysis for the diagnostic horizons, three distinct groups were formed: Latossolos Amarelos, Plintossolos Pétricos and Latossolos Vermelhos.

Keywords: *soil degradation, pedogenesis, soil attributes, principal components*

Introduction

Brazil has 162.19 million ha of pasture, corresponding to 19% of the territory. It has the largest commercial cattle herd in the world, with 214.69 million head, accounting for 8.7% of GDP. Among the Brazilian municipalities, Porto Velho is in seventh place with 968,778 heads (ABIEC, 2019). Despite the large cattle production, most Brazilian pastures are being degraded, due to the inadequate management adopted (Neves Junior et al., 2013) and the low knowledge about the soils present in the regions. In general, the state of Rondônia has several classes of soils and most of them have low fertility (Schlindwein et al., 2012), in addition to the fact that most soil survey studies in Porto Velho (state's capital) are old and low to medium intensity (Wittern and Conceição et al., 1982; Amaral et al., 2000).

Soil attributes are influenced by interactions between factors and processes of soil formation (Jenny, 1941), giving rise to different soil orders, which can be modified by anthropic actions (Saglam and Dengiz, 2012). The relief and the climate are factors of formation that can contribute to a greater degree of pedogenetic development of the soils. In turn, the relief is expressed by the degree of slope, which affects soil temperature, water content, groundwater level and the intensity of sediment removal and deposition processes (Chagas et al., 2013). So, depending on the position in the landscape, the relief can favor a process of rejuvenation in the soils (Lybrand and Rasmussen, 2018), causing environmental restrictions on the development of vegetation (Lopes et al., 2016). The climate itself is expressed by rainfall, temperature and air humidity, which affect the weathering process and the evolution of the profile (Pinheiro Junior et al., 2019).

To study the effect of the relief on the profiles of soils formed from the same parent material, the term catena (Milne, 1947) was used, in current works the term toposequence has usually been used, which makes it possible to consider more than one parent material. Studies have used toposequence to study the soil-landscape fauna relationship (Corrêa Neto et al., 2018), soil attributes and relationship with the tree community (Rodrigues et al., 2016), spatial variability of soil attributes (Capoane et al., 2017) and the behavior of soil attributes in transition areas between natural countryside - Forest (Campos et al., 2012). Conversely, other authors have used toposequence to characterize and classify soils, such as Campos et al. (2010), who studied soil attributes in the Amazon region and observed that the relief variations favor the presence of dystrophic soils located in the top area, and eutrophic soils in regions at the foot of the slope. Likewise, Guimarães et al. (2013) studying Gleissolos from the Rio Solimões floodplain in the state of Amazonas, concluded that the profiles of Gleissolos show variations in the fourth categorical level of their taxonomic classification and considerable difference in terms of physical and chemical attributes.

Thus, due to the ecological issues that the Amazon Forest weighs in Brazil and in the world, studies are needed to assess the impacts caused to the soil by converting forests into cultivated environments in the region, as a way of generating information that minimizes the impacts caused by agriculture (Lima et al., 2021). Thus, the objective of this work was to characterize, classify and evaluate the fragility of soils when used as pastures in a toposequence in the district of União Bandeirantes, Porto Velho, Rondônia.

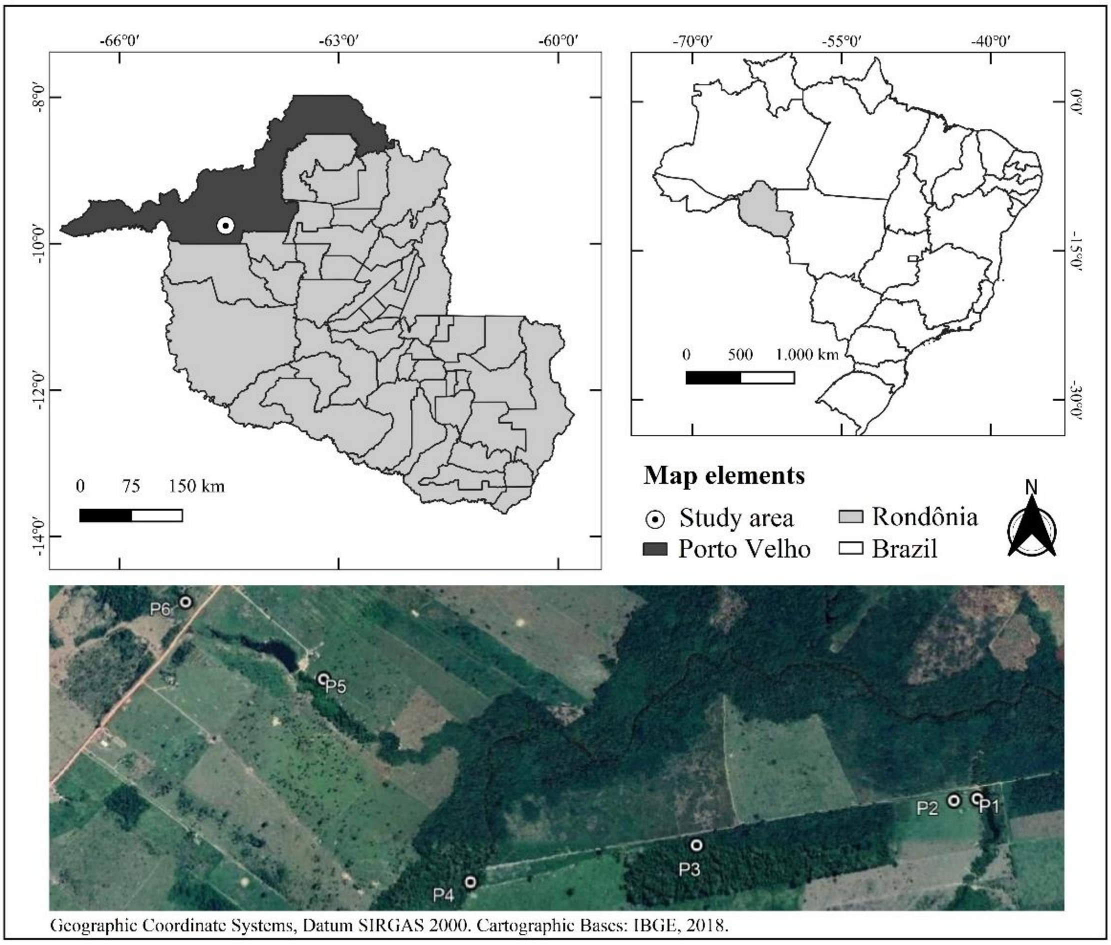
Materials and methods

Characterization of the studied areas

The study was developed in the União Bandeirantes district, located in the municipality of Porto Velho, Rondônia, Brazil. The study area is located on the Tabuleiros of the Amazon depression, the regional relief has a smooth wavy surface, with an altitude ranging from 100 to 200 m. (*Fig. 1; Table 1*).

The region's climate, according to the Köppen classification, belongs to group A (rainy tropical) and climate type Am (monsoon rains), with a short dry season between June and September. The annual rainfall ranges from 2,500 to 2,800 mm, the average annual temperature is between 24 to 26°C. The relative humidity is quite high, varying between 85% to 90% in the rainy season and 60 to 70% in the dry season (Alvares et al., 2013). The vegetation is called dense ombrophilous forest, consisting of dense and multi-layered trees between from 25 to 30 meters in height (Perigolo et al., 2017).

The profiles, P1 to P5, come from the Cenozoic era, from the Tertiary-Quaternary period. They are developed from undifferentiated sedimentary coverings, associated with environments of alluvial fans, fluvial channels, flood plains and lakes, constituted by sediments whose granulometry varies from gravel to clay, with significant lateritization. The P6 profile originated in the paleoproterozoic-mesoproterozoic era. They belong to the complex gneiss-migmatitic Jaru group, characterized by a remarkable tectonic suckling of lithotypes in medium to high grade metamorphic conditions, involving granitic orthogneisses, banded gneisses, paraderivated gneisses, amphibolites, mafic granulites and anatexia granites, among others (Adamy, 2010).



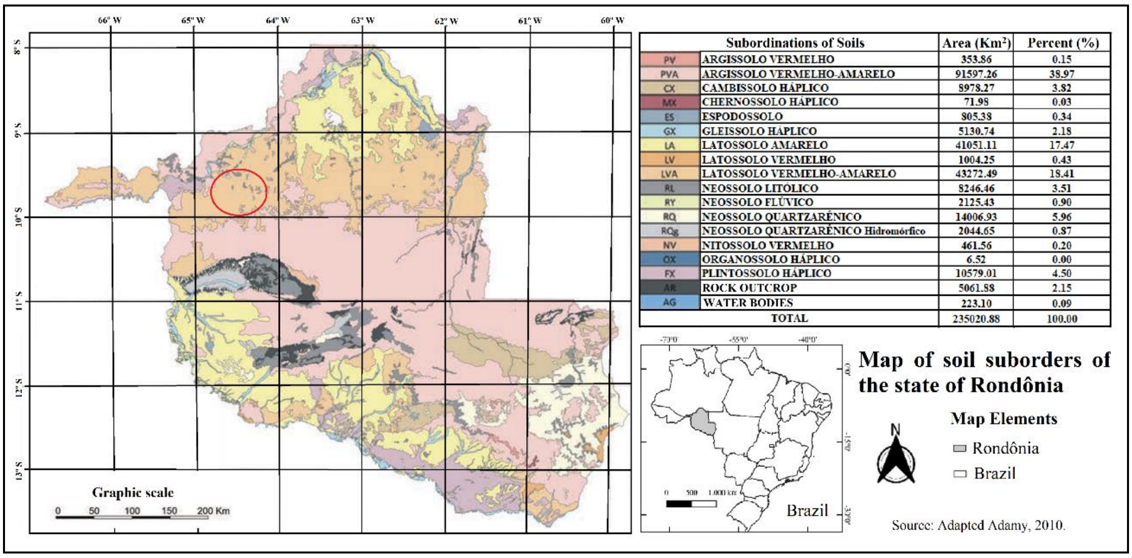
Geographic Coordinate Systems, Datum SIRGAS 2000. Cartographic Bases: IBGE, 2018.

Figure 1. *Location map of the study area in a toposequence under sandstone/gneiss in União Bandeirantes, Porto Velho, Rondônia*

The predominant soils in the study region are Latossolos, Argissolos and Plintossolos. Within the order of the Latossolo, the suborder of the Latossolo Vermelho-Amarelos occupies 18.41% of the territory, for the Argissolos, the suborder Argissolo Vermelho-Amarelo occupies 38.97% of the territory and the Plintossolos occupy 4.50% of the territory of Rondônia (*Fig. 2*).

Table 1. *Main characteristics of the soils studied in a toposequence in União Bandeirantes, Porto Velho, RO*

Profile	Coordinate	Altitude (m)	Local relief	Landscape position	Drainage	Current use
P1	S 09° 45’ 3.64” W 64° 31’ 38.94”	124	Smooth wavy	Lower third	Well drained	Riparian forest
P2	S 09° 45’ 4.17” W 64° 31’ 42.10”	128	Smooth wavy	Middle third	Well drained	Pasture
P3	S 09° 45’ 9.49” W 64° 32’ 17.12”	137	Flat	Top	Well drained	Forest
P4	S 09° 45’ 13.71” W 64° 32’ 47.16”	128	Wavy	Middle third	Moderately drained	Forest
P5	S 09° 44’ 45.74” W 64° 33’ 7.51”	134	Smooth wavy	Top	Moderately drained	Pasture
P6	S 09° 44’ 34.14” W 64° 33’ 27.36”	132	Smooth wavy	Foot	Well drained	Pasture



Subordinations of Soils		Area (Km²)	Percent (%)
PV	ARGISSOLO VERMELHO	353.86	0.15
PVA	ARGISSOLO VERMELHO-AMARELO	91597.26	38.97
CX	CAMBISSOLO HÁPLICO	8978.27	3.82
MX	CHERNOSSOLO HÁPLICO	71.98	0.03
ES	ESPODOSSOLO	805.38	0.34
GX	GLEISSOLO HÁPLICO	5130.74	2.18
LA	LATOSSOLO AMARELO	41051.11	17.47
LV	LATOSSOLO VERMELHO	1004.25	0.43
LVA	LATOSSOLO VERMELHO-AMARELO	43272.49	18.41
RL	NEOSSOLO LITÓLICO	8246.46	3.51
RY	NEOSSOLO FLÚVICO	2125.43	0.90
RQ	NEOSSOLO QUARTZARÊNICO	14006.93	5.96
RQg	NEOSSOLO QUARTZARÊNICO Hidromórfico	2044.65	0.87
NV	NITOSSOLO VERMELHO	461.56	0.20
OX	ORGANOSSOLO HÁPLICO	6.52	0.00
FX	PLINTOSSOLO HÁPLICO	10579.01	4.50
AR	ROCK OUTCROP	5061.88	2.15
AG	WATER BODIES	223.10	0.09
TOTAL		235020.88	100.00

Figure 2. *Soil map of the state of Rondônia, classification at the sub-category level (adapted from Adamy, 2010)*

Over time, successive fires have cleared the forest and formed the pasture areas present. The fires provided the ease of cleaning for later sowing of forages. The area of P2 has twelve years of use and the area of P5 and P6 fifteen years of use with pasture, it is noteworthy that fertilization and liming practices were not carried out in any of the areas.

Profile selection and sample collection

A toposequence representative of the region in forest and pasture environments was selected, tracing a path from the pasture environment (*Fig. 3*). The profiles corresponding to each environment were selected based on the relief position (middle, lower and upper thirds, foothills), vegetation patterns (forest and pasture), pedological characteristics (texture, color and granulometry) and source material (*Table 1*).

In each pedoenvironment of the toposequence, trenches were opened for morphological characterization and sample collection for physical and chemical analysis of the soils. Horizon identification and morphological description were performed according to Santos et al. (2015), with sample collection in all horizons. Soils were classified according to the criteria established by the Brazilian Soil Classification System (SiBCS) (Santos et al., 2018) and by the World Reference Base for Soil Resources (WRB) (WRB, 2015).

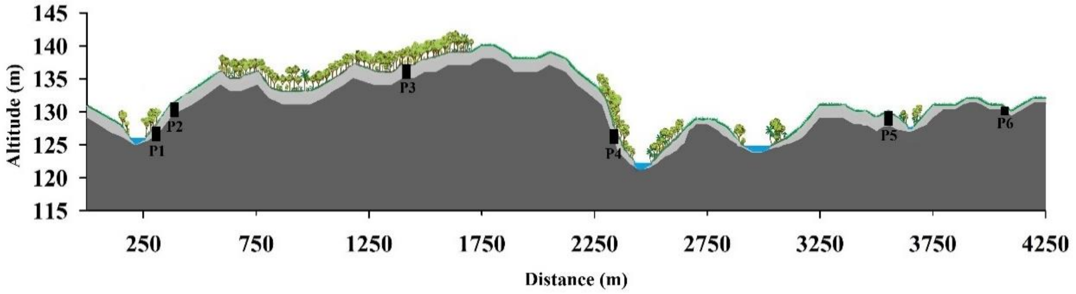


Figure 3. *Schematic altimetric profile showing vegetation, relief and the place of collection of soil profiles in a toposequence in the União Bandeirantes district, Porto Velho, Rondônia*

Laboratory analysis

After collected in the clod form and using volumetric cylinders, the soil sample were dried in the shade and lightly broken manually, followed by sifting through a 2.0 mm diameter mesh, composing the air-dried fine earth fraction (ADFE) required for laboratory analysis. ADFE was used to perform physical and chemical analyzes, according to Teixeira et al. (2017).

The soil texture was determined by the pipette method, with NaOH 1 mol L^{-1} solution as a chemical dispersant and mechanical agitation using the Wagner type agitator (Model MA160, Marconi), in a slow rotation apparatus for 16 h at 50 rpm. The coarse and fine sand fraction were separated by sifting, and the clay and silt fractions were separated by sedimentation. Additionally, the analysis of clay dispersed in water (CDW) was performed, and then the degree of flocculation (DF) was calculated through the proportion of the difference between the total clay and the CDW (Teixeira et al., 2017).

The soil density (Sd) was obtained by the method of the volumetric ring and the particle density (Pd) by the method of the volumetric balloon. Total porosity (Tp) was calculated from data on soil and particle densities, using the following equation: $Tp = 1-Sd/Pd$.

The pH in water and in KCl (1 mol L^{-1}) was determined potentiometrically using a Quimis G400MT benchtop pH meter, with a soil–solution ratio of 1:2.5 (Teixeira et al., 2017). Then, the ΔpH was calculated using *Equation 1*.

$$\Delta pH = pH\ (KCl) - pH\ (H_2O) \qquad \text{(Eq.1)}$$

Exchangeable calcium (Ca^{2+}), magnesium (Mg^{2+}) and aluminum (Al^{3+}) were extracted by KCl 1 mol L^{-1} solution. The contents of Al^{3+} were determined by titration, using NaOH 0.025 mol L^{-1} and bromothymol blue as a colorimetric indicator. The Ca^{2+} and Mg^{2+} contents were determined by atomic absorption spectrometry using the Thermo Scientific iCE 3300 ASS model. Potential acidity (H + Al) was determined with calcium acetate 0.5 mol L^{-1} buffered to pH 7.0 and determined by titration using

NaOH 0.025 mol L^{-1} and phenolphthalein as an indicator. The available potassium (K^+) and phosphorus (P) were extracted by Mehlich-1. P content was determined by a QUIMIS Q898UV-DB dual beam scanning UV-Vis spectrophotometer and K^+ content by flame spectrophotometry using a Model B462 flame photometer, Micronal. Based on the determinations of exchangeable cations and potential acidity were estimated: potential cation exchange capacity (CEC); sum of bases (SB), base saturation (V%), aluminum saturation (m%) and clay fraction activity (CEC_{clay}), according to Santos et al. (2018). Total organic carbon (TOC) was estimated by the method of Walkley and Black (1934), modified by Yeomans and Bremner (1988), using wet oxidation of organic matter with potassium dichromate and external heating, using diphenylamine (1%) as indicator and titrated with ammonium ferrous sulfate (0.102 mol L^{-1}).

Statistical analysis

Multivariate statistics were performed in the superficial and subsurface horizons, in order to assess the similarity between the profiles and observe which soil attributes that most characterize the studied environments. The software used was Statistica 7 (Statsoft, 2004).

To compare the similarity between the environments, Cluster analysis was used through the groupings by the hierarchical method, in which the Euclidean distance was used as a measure of similarity between profiles. The result of the analysis was presented in graphic form (dendrogram), which helped to identify the groupings of the profiles with the chemical and physical attributes of the analyzed soil. Based on the amalgamation schedule, the best Euclidean distance was chosen to form the groups.

Principal component analysis (PCA) was also performed to obtain the set of smaller linear combinations of the chemical and physical attributes of the soil, which preserves most of the information provided by the soil attributes (Silva et al., 2010). Principal component analysis allows qualitatively assessing interactions between soil attributes as a whole. For this, the values of the attributes were normalized to mean equal to zero and the variance equal to one. In choosing the number of components, we selected those that presented eigenvalues above 1.00 (Kaiser criterion) and that managed to synthesize an accumulated variance above 70%. The orthogonal rotation (varimax) was performed and represented in a factorial plane of the attributes and scores for the PCs, in order to simplify the factor analysis (Burak et al., 2010).

Results

Morphological attributes

Through the data shown in *Table 2*, we found in the profiles P1 to P5 a monochromatic pattern between the horizons, with a predominance of the 10 YR hue yellowish-bruno color for the wet samples and yellow to yellow-brunoish color in the droughts. For P6, a 5 YR hue was observed only for the dry samples in the Ap horizon and 2.5 YR for the other horizons in dry or damp materials.

The soil profiles did not differ abruptly in terms of textural class, with a texture varying from sand clay loam to very clayey. As for the surface horizons of P1, P2, P3 and P5, a sandy clay loam texture was found, while in P4 and P6 a clay texture was observed. The subsurface horizons of P1, P2, P3 and P5 have a sandy-clay texture, a very clayey in P4 and a clayey in P6.

Table 2. *Morphological characteristics of soil profiles in a toposequence under sandstone/gneiss in União Bandeirantes, Porto Velho, Rondônia*

Horizons	Depth (cm)	Color			Texture	Structure	Consistency	Transition
		Dry	Damp	Mottled			Damp and Wet	
Profile 1 - LATOSSOLO AMARELO Distrófico típico, A moderado, clayey texture – Riparian forest/Haplic FERRALSOL (Alumic, Clayic)								
A	0-7	10YR 4/3	10YR 2/2	-	Sandy clay loam	mod. to str., sma. to mean, gran.	fri., slig. plas., slig. sti.	Clear and flat
AB	7-18	10YR 5/3	10YR 5/4	-	Sandy clay loam	str., mean to big, ang. bl.	fri., slig. plas., slig. sti.	Clear and wavy
BA	18-31	10YR 7/6	10YR 5/4	-	Sandy clay	str., mean to big, ang. bl.	fri., plas., sti.	Grad. and flat
Bw1	31-55	10YR 7/4	10YR 6/6	-	Sandy clay	str., big to vbig., ang. bl.	fri., vplas., vsti.	Grad. and flat
Bw2	55-92	10YR 7/6	10YR 5/6	-	Sandy clay	mod., mean to big, ang. bl.	fri., vplas., vsti.	Grad. and flat
Bw3	92-130	10YR 6/6	10YR 5/6	-	Sandy clay	mod., mean to big, ang. bl	fri., vplas., vsti.	Grad. and flat
Bw4	130-160 +	10YR 8/6	10YR 6/6	-	Sandy clay loam	mod., mean to big, ang. bl. to sub. bl.	fri., vplas., vsti.	-
Profile 2 - LATOSSOLO AMARELO Distrófico típico, clayey texture – Pasture/Haplic FERRALSOL (Alumic, Clayic)								
AB	0-11	10YR 7/4	10YR 3/4	5YR 4/6, lit., sm., diff.	Sandy clay loam	str., mean, ang. bl. to sub. bl.	fri., slig. plas., slig. sti.	Clear and flat
BA	11-25	10YR 6/6	10YR 4/4	5YR 4/6, co., lit., diff.	Sandy clay	str., mean, ang. bl. to sub. bl.	fri., slig. plas., slig. sti.	Grad. and flat
Bw1	25-50	10YR 7/4	10YR 5/6	-	Sandy clay	mod., sma. to mean, ang. bl. to sub. bl.	fri., plas., sti.	Grad. and flat
Bw2	50-90	10YR 7/4	10YR 4/6	-	Sandy clay	mod., sma. to mean, ang. bl.	fri., plas., sti.	Grad. and flat
Bw3	90-125	10YR 7/6	10YR 5/6	-	Sandy clay	mod., lit. to mean, ang. bl.	fri., plas., sti.	Grad. and flat
Bw4	125-150 +	10YR 7/4	10YR 5/6	-	Sandy clay	mod., lit. to mean, ang. bl.	fri., plas., sti.	-
Profile 3 - LATOSSOLO AMARELO Distrófico típico, A moderado, clayey texture – Forest/Haplic FERRALSOL (Alumic, Clayic)								
A	0-10	10YR 4/4	10YR 4/4	-	Sandy clay loam	str., lit. to mean, ang. bl. to sub. bl.	fri., slig. plas., slig. sti.	Grad. and flat
BA	10-25	10YR 6/6	10YR 5/6	-	Sandy clay	str., mean to big, ang. bl. to sub. bl.	fri., plas., sti.	Grad. and flat
Bw1	25-45	10YR 7/4	10YR 5/6	-	Sandy clay	str., big to vbig, ang. bl. to sub. bl.	fri., plas., sti.	Grad. and flat
Bw2	45-71	10YR 6/6	10YR 5/6	-	Sandy clay	str., big to vbig, ang. bl. to sub. bl.	vfri., plas., sti.	Grad. and flat
Bw3	71-95	10YR 6/6	10YR 5/6	-	Sandy clay	str., big to mbig, ang. bl. to sub. bl.	vfri., slig. plas., sti.	Grad. and flat
Bw4	95-122	10YR 7/6	10YR 5/6	-	Sandy clay	mod., mean to big, ang. bl. to sub. bl.	vfri., slig. plas., sti.	Grad. and flat
Bw5	122-150 +	10YR 7/6	10YR 5/6	-	Sandy clay	mod., lit. to mean, ang. bl. to sub. bl.	vfri., slig. plas., sti.	-
Profile 4 - PLINTOSSOLO PÉTRICO Concrecionário êndico, A moderado, distrófico, very clayey texture – Forest/Pisoplinthic PLINTHOSOL (Alumic, Clayic)								
A	0-5	10YR 4/4	10YR 4/4	-	Clayey	str., mean to big, ang. bl. to gran.	fri., slig. plas., slig. sti.	Grad. and Wavy
BA	5-17	10YR 5/6	10YR 5/6	-	Clayey	mod., lit. to mean., ang. bl. to sub. bl.	fri., plas., sti.	Grad. and Wavy
Bcf1	17-42	10YR 7/4	10YR 5/6	-	Clayey	mod., mean to big, ang. bl. to sub. bl.	fri., slig. plas., slig. sti.	Grad. and wavy
Bcf2	42-69	-	-	-	Clayey	-	-	Grad. and wavy
Bcf3	69-102	-	-	-	Clayey	-	-	Grad. and wavy
Bcf4	102-150 +	-	-	-	Clayey	-	-	-
Profile 5 - PLINTOSSOLO PÉTRICO Concrecionário êndico, A moderado, distrófico, clayey texture – Pasture/Pisoplinthic PLINTHOSOL (Alumic, Clayic)								
Ap	0-11	10YR 5/3	10YR 4/4	-	Sandy clay loam	mod., lit. to mean, ang. bl. to sub. bl.	fri., slig. plas., slig. sti.	Clear and flat
AB	11-29	10YR 5/6	10YR 3/4	-	Sandy clay	str., mean to big, ang. bl. to sub. bl.	fri., slig. plas., slig. sti.	Grad. and flat
BA	29-42	10YR 5/6	10YR 4/6	-	Sandy clay	str., mean to big, ang. bl. to sub. bl.	fri., plas., sti.	Clear and flat
Bw	42-72	10YR 7/6	10YR 4/6	-	Sandy clay	mod., lit. to mean, gran.	fri., plas., sti.	Clear and flat
Bcf1	72-109	10YR 7/6	10YR 5/6	-	Sandy clay	str., lit. to mean, ang. bl. to sub. bl.	fri., plas., sti.	Diff. and flat
Bcf2	109-148	10YR 6/6	10YR 5/6	-	Sandy clay	wk., vsm. to lit., ang. bl. to sub. bl.	fri., slig. plas., slig. sti.	Diff. and flat
Bf	148-160 +	10YR 6/6	10YR 5/6	-	Sandy clay	wk., lit., ang. bl.	fri., slig. plas., slig. sti.	-
Profile 6 - LATOSSOLO VERMELHO Distrófico cambissólico, A moderado, clayey texture – Pasture/Haplic FERRALSOL (Dystnic, Clayic)								
Ap	0-10	5YR 4/6	2.5YR 3/4	-	Clayey	str., mean to big, ang. bl. to sub. bl.	fri., plas., sti.	Grad. and flat
Bw1	10-28	2.5YR 3/6	2.5YR 2.5/4	-	Clayey	str., mean to big, ang. bl. to sub. bl.	fri., plas., sti.	Grad. and flat
Bw2	28-50	2.5YR 4/8	2.5YR 2.5/4	-	Clayey	str., mean to big, ang. bl. to sub. bl.	fri., slig. plas., slig. sti.	Grad. and flat
Bw3	50-72	2.5YR 4/8	2.5YR 2.5/4	-	Clayey	str., mean to big, ang. bl. to sub. bl.	fri., slig. plas., slig. sti.	-

(1) wk.: weak; mod.: moderate; str.: strong; sm.: small; vsm.: very small; vbig.: very big; gran.: granular; ang. bl.: angular blocks; and sub. bl.: subangular blocks; (2) vfri.: very friable; fri.: friable; slig. plas.: slightly plastic; plas.: plastic; vplas.: very plastic; slig. sti.: slightly sticky; sti.: sticky; and vsti.: very sticky; (3) cl.: clear; grad.: gradual; and diff.: diffuse; lit.: little; and co.: common

As for the structure, the superficial and subsurface horizons are under a wide degree of development that can vary from weak to strong, with sizes from small to very large and angular to granular blocks. In P1 and P4, granular structure was observed in the superficial horizon. The degree of weak development was observed only at P1 for the subsurface horizons Bcf2 and Bf. The structure of P6 did not show variation between its horizons, being of strong degree, size varying from medium to large in blocks from angular to sub-angular.

The consistency when wet, varied from very friable to friable, being observed friable consistency only for P3 from the horizon Bw2. As for the wet consistency, the plasticity varied from slightly plastic to very plastic and for stickiness there was a variation from slightly sticky to very sticky. Only at P1, a very sticky and very plastic consistency was observed from its Bw1 horizon. The transition between the horizons varied in terms of the degree of clear, gradual or diffuse sharpness, and in terms of its shape, it varied between flat and wavy.

Physical attributes

The results regarding the physical attributes are shown in *Table 3*. There is a predominance of the ADFE fraction in all profiles studied, except in P4 and P5, in which there was a predominance of the gravel fraction in the subsurface horizons, with values greater than 500 g kg^{-1}. In addition to petroplintite, the gravel fraction was also made up of quartz, being that in profiles P1, P2 and P3 we did not find any occurrence of petroplintite in the gravel fraction, which was composed only of quartz.

As for the granulometric composition of the ADFE fraction, there was a predominance of the sand fraction in P1, P2, P3 and P5, varying from 483 to 669 g kg^{-1}. In contrast, in P4 and P6 we found a predominance of the clay fraction, with contents between 408 to 676 g kg^{-1}. Regarding the sand fractions, there was a predominance of coarse sand in all profiles except for P6, in which the fine sand fraction predominated. Low levels of silt were found in all profiles, varying from 12 to 145 g kg^{-1}, where the highest levels are present in P6 and the lowest in P1, P2 and P3. The CDW showed high values in the superficial horizons, decreasing in the subsurface horizons until reaching 100% flocculation.

For the silt/clay ratio, values ranging from 0.03 to 0.36 were found, with the highest values observed in P6 (0.20-0.36) and the lowest values in P1, P2 and P3 (0.03- 0.12) indicating that these profiles have a higher degree of weathering.

The Sd values (soil density) range from 0.90 to 1.56 Mg m^{-3}, with the lowest values observed in P4 and the highest in the other profiles that did not differ between them. For Pd (particle density), the values ranged from 2.60 to 2.90 Mg m^{-3}, however, little variation was observed between profiles and horizons, indicating homogeneity between the studied environments.

For Tp, the values ranged from 0.45 to 0.68 m^3 m^{-3}, a pattern opposite to that observed for Sd, however it presented values above 0.50 m^3 m^{-3} for most of the studied superficial and subsurface horizons. This fact can be attributed to the soil’s granulometry, which is largely composed of the coarse sand fraction.

Chemical attributes

There are low pH values, high levels of Al^{3+}, H + Al and limited availability of nutrients such as Ca^{2+}, Mg^{2+}, K^+, Na^+ and P (*Table 4*). The lowest pH values in H_2O, Ca^{2+}, Mg^{2+}, K^+ and higher in Al^{3+} and H + Al were found in the forest areas (P1, P3 and

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P4) compared to pastures (P2, P5 and P5) in the superficial horizons. In all profiles, the pH values in H_2O and KCl ranged from 3.80 to 5.77 and 3.46 to 4.69, respectively. For all horizons in all profiles, the pH values in KCl were lower than the pH in water, establishing a negative ΔpH (-1.20 to -0.33), showing a predominance of negative charges. Higher levels of exchangeable bases (Ca^{2+}, Mg^{2+}, K^+, Na^+) were observed in the superficial horizons compared to the subsurface, and consequently, also greater SB and V%, which ranged from 0.25 to 3.44 $cmol_c\ kg^{-1}$ and 4.85 to 45.32%, respectively.

Table 3. *Physical characterization of soil profiles in a toposequence under sandstone/gneiss in União Bandeirantes, Porto Velho, Rondônia*

Horiz.	Depth	Gravel	ADFE	Total sand	Coarse sand	Fine sand	Silt	Clay	CDW	DF	S/C	Sd	Dp	Tp
	cm	g kg^{-1}								%		Mg m^{-3}		$m^3\ m^{-3}$
Profile 1 - LATOSSOLO AMARELO Distrófico típico, A moderado, clayey texture – Riparian forest Haplic FERRALSOL (Alumic, Clayic)														
A	0-7	44	956	669	448	221	35	296	220	25	0.12	1.13	2.63	0.57
AB	7-18	47	953	644	400	244	34	322	201	37	0.11	1.34	2.89	0.54
BA	18-31	47	953	593	377	216	33	374	312	17	0.09	1.51	2.90	0.48
Bw1	31-55	43	957	603	392	211	30	367	62	83	0.08	1.46	2.90	0.50
Bw2	55-92	38	962	593	367	226	12	395	0	100	0.03	1.46	2.82	0.48
Bw3	92-130	33	967	617	399	218	13	370	0	100	0.04	1.42	2.89	0.51
Bw4	130-160 +	44	956	634	439	195	29	337	0	100	0.09	1.39	2.90	0.52
Profile 2 - LATOSSOLO AMARELO Distrófico típico, clayey texture – pasture Haplic FERRALSOL (Alumic, Clayic)														
AB	0-11	39	961	657	408	249	28	315	257	18	0.09	1.44	2.83	0.49
BA	11-25	37	963	601	385	216	18	381	312	18	0.05	1.56	2.86	0.45
Bw1	25-50	37	963	574	355	219	40	386	34	91	0.10	1.47	2.77	0.47
Bw2	50-90	59	941	556	307	249	36	408	0	100	0.09	1.41	2.60	0.46
Bw3	90-125	48	952	557	333	224	39	404	0	100	0.10	1.40	2.90	0.52
Bw4	125-150 +	39	961	566	332	234	30	404	0	100	0.07	1.36	2.92	0.54
Profile 3 - LATOSSOLO AMARELO Distrófico típico, A moderado, clayey texture – Forest Haplic FERRALSOL (Alumic, Clayic)														
A	0-10	11	989	644	470	174	34	322	256	20	0.11	1.16	2.74	0.58
BA	10-25	9	991	568	371	197	34	398	341	14	0.09	1.45	2.83	0.49
Bw1	25-45	12	988	528	345	183	25	447	391	13	0.06	1.37	2.72	0.50
Bw2	45-71	11	989	520	350	170	23	457	0	100	0.05	1.47	2.90	0.49
Bw3	71-95	15	985	530	345	185	28	442	0	100	0.06	1.38	2.83	0.51
Bw4	95-122	18	982	529	361	168	48	423	0	100	0.11	1.39	2.90	0.52
Bw5	122-150 +	13	987	483	302	181	46	471	0	100	0.10	1.43	2.90	0.51
Profile 4 - PLINTOSSOLO PÉTRICO Concrecionário êndico, A moderado, distrófico, very clayey texture – Forest Pisoplinthic PLINTHOSOL (Alumic, Clayic)														
A	0-5	49	951	405	269	136	107	488	408	16	0.22	0.90	2.77	0.68
BA	5-17	479	521	251	146	105	133	616	295	52	0.22	-	2.90	-
Bcf1	17-42	575	425	235	143	92	89	676	0	100	0.13	-	2.89	-
Bcf2	42-69	618	382	270	164	106	93	637	0	100	0.15	-	2.87	-
Bcf3	69-102	641	359	278	178	100	74	648	0	100	0.11	-	2.90	-
Bcf4	102-150 +	647	353	301	198	103	63	636	0	100	0.10	-	2.90	-
Profile 5 - PLINTOSSOLO PÉTRICO Concrecionário êndico, A moderado, distrófico, clayey texture – Pasture Pisoplinthic PLINTHOSOL (Alumic, Clayic)														
Ap	0-11	41	959	621	409	212	55	324	275	15	0.17	1.36	2.84	0.52
AB	11-29	37	963	523	318	205	54	423	372	12	0.13	1.43	2.90	0.51
BA	29-42	40	960	484	281	203	63	453	415	8	0.14	1.42	2.90	0.51
Bw	42-72	38	962	471	279	192	56	473	8	98	0.12	1.16	2.90	0.60
Bcf1	72-109	490	510	474	289	185	39	487	0	100	0.08	-	2.90	-
Bcf2	109-148	847	153	492	310	182	40	468	0	100	0.08	-	2.90	-
Bf	148-160 +	361	639	557	402	155	47	396	0	100	0.12	-	2.90	-
Profile 6 - LATOSSOLO VERMELHO Distrófico cambissólico, A moderado, clayey texture – Pasture Haplic FERRALSOL (Dystnic, Clayic)														
Ap	0-10	25	975	447	181	266	145	408	262	36	0.36	1.26	2.89	0.56
Bw1	10-28	23	977	387	139	248	101	512	0	100	0.20	1.14	2.88	0.60
Bw2	28-50	38	962	391	157	234	109	500	0	100	0.22	1.17	2.90	0.60
Bw3	50-72 +	92	908	377	148	229	131	492	0	100	0.27	1.14	2.90	0.61

CDW: clay dispersed in water; DF: degree of flocculation; S/C: silt/clay ratio; Sd: soil density; Pd: particle density; Tp: total porosity

Table 4. *Chemical characterization of soil profiles in a toposequence under sandstone/gneiss in União Bandeirantes, Porto Velho, Rondônia*

Horizon	**Depth**	**pH**		**ΔpH**	**Ca^{2+}**	**Mg^{2+}**	**K^{+}**	**Na^{+}**	**SB**	**Al^{3+}**	**H + Al**	**CEC**	**CEC_{clay}**	**V**	**m**	**P**	**TOC**
	cm	**H_2O**	**KCl**		**$cmol_c$ Kg^{-1}**									**%**		**mg kg^{-1}**	**g kg^{-1}**
Profile 1 - LATOSSOLO AMARELO Distrófico típico, A moderado, clayey texture – Riparian forest/Haplic FERRALSOL (Alumic, Clayic)																	
A	0-7	4.51	3.77	-0.74	0.29	0.18	0.18	0.05	0.70	1.77	9.31	10.01	-	6.99	71.66	3.72	29.94
AB	7-18	4.35	3.77	-0.58	0.28	0.11	0.10	0.02	0.51	1.92	7.20	7.71	-	6.61	79.01	2.21	17.56
BA	18-31	4.36	3.88	-0.48	0.25	0.06	0.03	0.01	0.35	1.20	3.44	3.79	10.13	9.23	77.42	0.81	9.92
Bw1	31-55	4.32	3.89	-0.43	0.27	0.06	0.03	0.01	0.37	1.01	3.60	3.97	10.82	9.32	73.19	0.48	10.93
Bw2	55-92	4.21	3.90	-0.31	0.25	0.05	0.01	nd	0.31	1.15	3.60	3.91	9.90	7.93	78.77	0.34	6.76
Bw3	92-130	4.33	4.00	-0.34	0.23	0.05	0.01	nd	0.29	0.91	2.66	2.95	7.97	9.83	75.83	0.27	6.38
Bw4	130-160^{+}	4.59	4.13	-0.46	0.24	0.04	nd	nd	0.28	0.86	2.27	2.55	7.57	10.98	75.44	0.16	6.06
Profile 2 - LATOSSOLO AMARELO Distrófico típico, clayey texture – Pasture/Haplic FERRALSOL (Alumic, Clayic)																	
AB	0-11	5.53	4.33	-1.20	1.06	0.20	0.28	0.02	1.56	0.57	3.60	5.16	-	30.23	26.76	1.24	15.03
BA	11-25	5.03	4.08	-0.95	0.69	0.11	0.05	0.01	0.86	0.57	3.44	4.30	11.29	20.00	39.86	0.55	10.86
Bw1	25-50	4.81	4.18	-0.63	0.32	0.05	0.09	nd	0.46	0.96	3.05	3.51	9.09	13.11	67.61	0.45	8.08
Bw2	50-90	4.63	4.16	-0.47	0.29	0.05	0.02	nd	0.36	1.25	3.44	3.80	9.31	9.47	77.64	0.48	6.19
Bw3	90-125	4.76	4.17	-0.59	0.31	0.04	0.02	nd	0.37	1.15	2.58	2.95	7.30	12.54	75.66	0.19	6.69
Bw4	125-150^{+}	4.87	4.21	-0.66	0.31	0.05	nd	nd	0.36	0.81	1.88	2.24	5.54	16.07	69.23	0.19	6.32
Profile 3 - LATOSSOLO AMARELO Distrófico típico, A moderado, clayey texture – Forest/Haplic FERRALSOL (Alumic, Clayic)																	
A	0-10	4.03	3.52	-0.51	0.29	0.12	0.08	nd	0.49	1.82	7.04	7.53	-	6.51	78.79	3.32	16.67
BA	10-24	4.22	3.78	-0.44	0.23	0.06	0.02	nd	0.31	1.72	5.40	5.71	14.35	5.43	84.73	0.95	12.44
Bw1	25-45	4.31	3.81	-0.51	0.27	0.06	0.01	0.01	0.35	1.63	4.38	4.73	10.58	7.40	82.32	0.52	11.37
Bw2	45-71	4.51	3.98	-0.53	0.27	0.06	0.01	nd	0.34	1.44	3.76	4.10	8.97	8.29	80.90	0.45	9.35
Bw3	71-95	4.58	4.07	-0.51	0.25	0.04	nd	nd	0.29	1.39	3.37	3.66	8.28	7.92	82.74	0.19	8.84
Bw4	95-122	4.41	4.08	-0.33	0.25	0.04	nd	nd	0.29	1.39	3.05	3.34	7.90	8.68	82.74	0.09	7.33
Bw5	122-150^{+}	4.49	4.10	-0.39	0.25	0.04	nd	nd	0.29	1.44	2.66	2.95	6.26	9.83	83.24	0.09	5.56
Profile 4 - PLINTOSSOLO PÉTRICO Concrecionário êndico, A moderado distrófico, very clayey texture – Forest/Pisoplinthic PLINTHOSOL (Alumic, Clayic)																	
A	0-5	3.80	3.46	-0.35	0.31	0.12	0.15	0.01	0.59	2.68	11.58	12.17	-	4.85	81.96	5.48	33.09
BA	5-17	4.53	4.02	-0.51	0.23	0.38	0.04	nd	0.65	1.39	5.09	5.74	9.32	11.32	68.14	1.20	14.21
Bcf1	17-42	4.68	4.10	-0.59	0.22	0.06	0.02	nd	0.30	1.39	3.99	4.29	6.35	6.99	82.25	0.59	11.43
Bcf2	42-69	4.81	4.17	-0.65	0.22	0.05	0.01	nd	0.28	0.91	2.97	3.25	5.10	8.62	76.47	0.19	9.09
Bcf3	69-102	4.99	4.18	-0.82	0.25	0.04	nd	nd	0.29	0.86	3.13	3.42	5.28	8.48	74.78	0.16	7.52
Bcf4	102-150^{+}	5.01	4.21	-0.80	0.20	0.05	nd	nd	0.25	0.96	2.19	2.44	3.84	10.25	79.34	0.23	7.07
Profile 5 - PLINTOSSOLO PÉTRICO Concrecionário êndico, A moderado, distrófico, clayey texture – Pasture/Pisoplinthic PLINTHOSOL (Alumic, Clayic)																	
Ap	0-11	4.73	3.95	-0.78	0.60	0.09	0.05	0.01	0.75	0.53	5.24	5.99	-	12.52	41.41	1.20	17.56
AB	11-29	4.76	3.96	-0.80	0.53	0.05	0.03	0.01	0.62	1.10	4.38	5.00	-	12.40	63.95	0.55	13.77
BA	29-42	4.61	3.98	-0.64	0.36	0.05	0.01	nd	0.42	1.29	4.85	5.27	11.63	7.97	75.44	0.59	12.25
Bw	42-72	4.71	3.97	-0.74	0.28	0.05	0.01	nd	0.34	1.20	2.82	3.16	6.68	10.76	77.92	0.37	8.53
Bcf1	72-109	4.90	4.02	-0.88	0.28	0.05	nd	nd	0.33	1.10	2.66	2.99	6.14	11.04	76.92	0.37	7.39
Bcf2	109-148	5.06	4.12	-0.94	0.23	0.04	0.01	nd	0.28	0.91	2.19	2.47	5.28	11.34	76.47	0.23	6.32
Bf	148-160^{+}	5.10	4.22	-0.89	0.23	0.04	nd	0.01	0.28	0.67	1.33	1.61	4.07	17.39	70.53	0.27	5.62
Profile 6 - LATOSSOLO VERMELHO Distrófico cambissólico, A moderado, clayey texture – Pasture/Haplic FERRALSOL (Dystnic, Clayic)																	
Ap	0-10	5.77	4.69	-1.08	2.27	0.86	0.30	0.01	3.44	0.24	4.15	7.59	-	45.32	6.52	0.91	19.07
Bw1	10-28	5.20	4.22	-0.98	0.51	0.46	0.07	0.01	1.05	0.53	4.85	5.90	11.52	17.80	33.54	0.55	12.19
Bw2	28-50	5.31	4.27	-1.04	0.28	0.54	0.06	0.01	0.89	0.48	4.07	4.96	9.92	17.94	35.04	0.70	9.85
Bw3	50-72^{+}	5.34	4.43	-0.91	0.23	0.52	0.07	0.01	0.83	0.24	3.44	4.27	8.68	19.44	22.43	0.55	10.04

nd: not detected; SB: sum of bases; CEC: cation exchange capacity; CEC_{Clay}: Clay fraction activity; V: base saturation; and m: aluminum saturation

The contents of Al^{3+} and H + Al were obtained between 0.24 to 2.68 and 1.33 to 11.58 $cmol_c$ kg^{-1}, respectively. For Al^{3+}, the highest values were quantified in P4 and the lowest in P6, between horizons. Its lowest values, in large part, occurred in the superficial horizons in relation to the subsurface. For H + Al, the highest concentrations were obtained in the superficial horizons, mainly in P4, and the lowest in P2, the inverse relationship to that found for Al^{3+}.

The aluminum saturation was greater than 50% for the profiles from P1 to P5, indicating that these soils are acidic. P6 and the surface horizons of P2 and P5 differ from this pattern, as they concentrate less than 50% of the saturation, indicate that these soils are non-alic.

The available P levels ranged from 0.16 to 5.48 mg kg^{-1}, with the highest levels found in P4. In addition, it is noted that the highest levels were found in forest environments compared to pasture areas for superficial horizons, with levels decreasing in depth. In general, the highest levels of organic carbon were quantified in the superficial horizons in all profiles, decreasing in depth. These levels ranged from 5.56 to 33.90 g kg^{-1} in the forest areas and from 5.62 to 19.07 g kg^{-1} under pasture.

Multivariate analysis

In the cluster analysis, using the chemical and physical attributes together, we used the Amalgamation scheme to separate the groups considering a Euclidean distance of 170 for the surface horizon and 470 for the subsurface horizon (*Fig. 4*). The formation of three groups was observed in the surface horizon, with GI and GII represented by P6 and P4, respectively. The opposite result can be observed in GIII formed by profiles P1, P2, P3 and P5 (*Fig. 4A*). In the subsurface horizon, two groups were formed, the GI represented by the Plinthosols (PLINTOSOL) (P4 and P5) and the GII represented by the Oxisols (FERRALSOL) (P1, P2, P3 and P6).

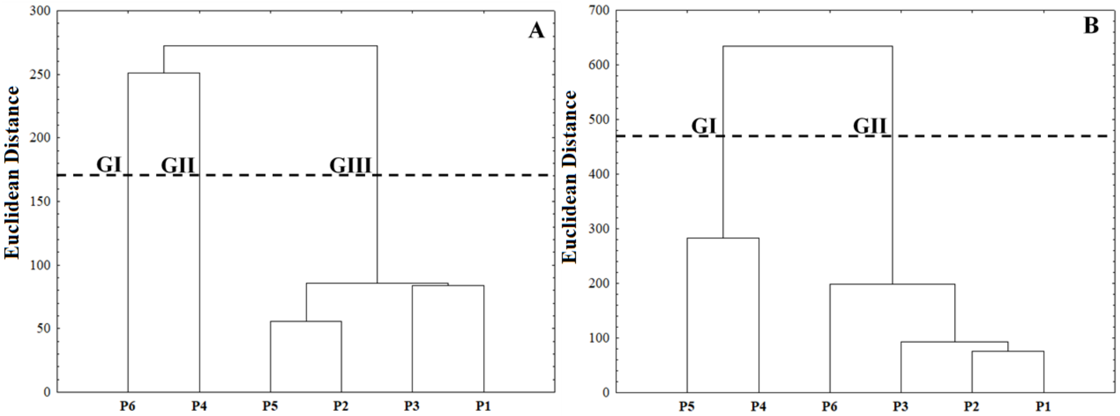


Figure 4. *Dendrogram resulting from the cluster analysis of soil classes represented in a toposequence under sandstone/gneiss in the União Bandeirantes district, Porto Velho, Rondônia, in the superficial horizon (A) and in the subsurface (B)*

The principal components analysis for the superficial horizons allowed the reduction of the number of variables, grouping 15 original variables in two factors (*Fig. 5A*). The factors are able to explain 92.60% of the variance of the variables with eigenvalues greater than 1. PC1 explains 64.38%, being responsible for the attributes related to acidity (pH in H_2O and KCl, ΔpH, Al^{3+}, H + Al), CEC, P, TOC, fine sand, Sd and Tp; PC2 explains 28.22%, being responsible for explaining the exchangeable bases (Ca^{2+} and Mg^{2+}) and the granulometric fractions (coarse sand, silt and clay). In PC1, ΔpH, Al^{3+}, H + Al, CEC, P, TOC and Tp showed positive values while pH in H_2O and KCl, fine sand and Sd, negative values, indicating that the attributes that showed the same signs have a direct correlation, while the that have opposite signs have an inverse correlation. In PC2, Ca^{2+}, Mg^{2+}, silt and clay showed positive values, while coarse sand was negative. Through the analysis of the factorial plane, 3 groups were formed in the superficial horizons, the first formed by P1, P3 and P5 being discriminated by the coarse sand; The second composed by P2 and P6 which is characterized by Ca^{2+}, Mg^{2+}, pH in H_2O and KCl, fine sand and Sd; and finally group three belonging to P4 and discriminated by clay, silt, Tp, CEC, TOC, H + Al, P, Al^{3+} and ΔpH.

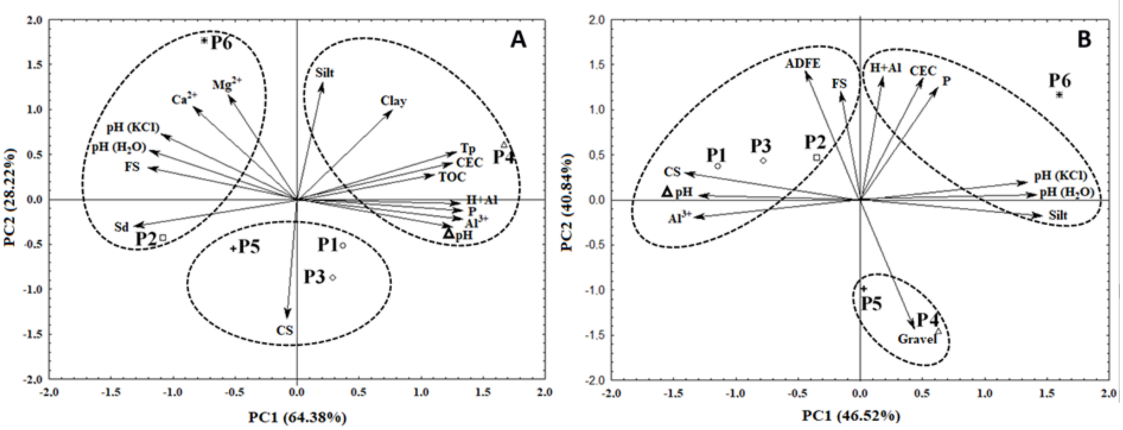


Figure 5. *Principal component analysis for the superficial (A) and subsurface (B) horizons of the soils studied in a toposequence in the União Bandeirantes district, Porto Velho, Rondônia*

When analyzing the principal components for the subsurface horizons, it is observed that these were reduced to 12 original variables in two factors (*Fig. 5B*). Being able to explain 87.36% of the variance of variables with eigenvalues greater than 1. PC1 explains 46.52%, being responsible for the attributes: pH in H_2O and KCl, ΔpH, Al^{3+}, coarse sand and silt; PC2 explains 40.84% of the variance, being responsible for H + Al, CEC, P, ADFE, gravel and fine sand. In PC1, pH in H_2O and KCl and silt showed positive values while ΔpH, Al^{3+} and coarse sand presented negative values, this indicates that the attributes that showed the same signs have a direct correlation while those that have opposite signs have an inverse correlation. In PC2, H + Al, CEC, P, ADFE and fine sand showed positive values, while the gravel was negative. When evaluating the factorial plane of the subsurface horizons, we verified the formation of three groups, the first group belonging to the Latossolos Amarelos, being composed of P1, P2 and P3 being discriminated by ADFE, fine and coarse sand, ΔpH and Al^{3+}; The second group belongs to the Plintossolos Pétricos, formed by P4 and P5 and distinguished only by the gravel; and finally the third group formed by P6 belonging to the Latossolo Vermelho, which is discriminated by H + Al, CEC, P, pH in H_2O and KCl and silt.

Discussion

Soil characterization

The yellowish colors observed in P1 to P5 are due to the nature of the parent material, which has a small contribution of ferromagnesian minerals in its composition, also to the degree of weathering and pedogenetic processes that contribute to the accumulation or removal of Fe (Santos et al., 2010). Humid environments with low iron content favor greater formation of goethite to the detriment of hematite, providing a yellow color to the soil (Kämpf and Curi, 2000). On the other hand, the reddish color observed in P6 is due to the parent material that has higher levels of ferromagnesian minerals in the parent material. In P2, it is due to the conditions of hydromorphism, confirmed by the presence of mottled (few, small and diffuse) in the AB and BA horizons. This pattern may be indicative of micromorphological variations provided by the microrelief, which generates regions of oxidation forming the mottled.

The characteristics of the granulometric composition of the ADFE fraction are due to the parent material that, because they are sedimentary coverings with granulometry ranging from gravel to clay and a significant lateritization, favor this behavior as highlighted by Adamy (2010). In general, it was possible to observe the predominance of the sand fraction in the superficial horizons and an insignificant increase of clay in the subsurface horizons in comparison to the superficial one. This is due to the exposure of the soil surface to the impacts of rain, favoring the destruction of aggregates, individualizing the particles and intensifying the process of selective erosion of smaller diameter particles (clay) (Shi et al., 2017).

The high levels of CDW and low DF in the superficial horizons may be related to the characteristics of the clay present in the system and probably to the higher content of organic matter on the surface, which when decomposed can contribute to the increase of the electrical loads of the soil, reducing the activity of elements responsible for the aggregation and flocculation of these particles (Guimarães et al., 2013). In addition, this can also be attributed to the high levels of aluminum in the superficial horizons and the exudation of substances by the roots of the plants (Alleoni and Camargo, 1994).

According to Jacomine (2005), the higher the S/C ratio, the less weathered the soil is. Pereira et al. (2013) explain that in horizons with clayey texture, values below 0.6 indicate a high degree of weathering.

The high Sd values are associated with higher levels of sand, corroborating the work of Giarola et al. (2002), who observed a positive correlation between Sd and the sand fraction. The lowest Sd values were observed in the superficial horizons, which according to Martins et al. (2006) and Franciscon et al. (2019) when faced with this same pattern, they are due to the higher levels of organic matter. The compaction of soils in the subsurface horizons can be attributed to the pressure exerted by the superficial horizons and by the increase in the clay content in depth, corroborating with Campos et al. (2012) and Franciscon et al. (2019).

Through the results of chemical analyzes, it appears that the soils are dystrophic and alic, which is likely to be a result of the strong leaching of bases in these profiles due to the intense and frequent rains occurring in the Amazon rainforest (Freitas et al., 2013).

In pasture areas, the soils are less acidic and have higher levels of nutrients (Ca^{2+}, Mg^{2+}, K^+), probably due to soil management, as the use of fire to remove forests is very common in this region and the ashes deposited in the soil increases pH values and nutrient availability (Araújo et al., 2011; Braz et al., 2013; Zenero et al., 2016).

The cation exchange capacity (CEC) exceeds the anion exchange capacity (AEC) under natural pH conditions (Fernandes et al., 2008). The negative ΔpH value in Amazonian soils is largely due to the predominance of kaolinitic and oxidic mineralogy of these soils (Souza et al., 2018). This result was also observed by Carvalho et al. (2007), who studied changes in chemical attributes in Latossolo after removal of native vegetation for agricultural use in Vilhena, Rondônia. The high negative values of ΔpH were observed in the profiles on pastures, corroborating the pattern verified by Zenero et al. (2016), who also found the highest values in areas under pasture in Amazonas.

The better fertility of the soil in the superficial horizons is attributed to the addition of organic matter in the soil surface and higher CEC that were also observed in the superficial horizons varying from 1.61 to 12.17 $cmol_c\ kg^{-1}$. This pattern was also observed by Kweon et al. (2013) and Franciscon et al. (2019), who attributed the high CEC value in the superficial horizons of the soil to organic matter. Regarding the profiles, we observed greater fertility in P6 (Latossolo Vermelho) when compared to the others, we attribute this to the parent material, formed from metamorphic rocks (Adamy, 2010).

Despite being alics (except P6), the soils have low aluminum content, being less than 5.5 $cmol_c\ kg^{-1}$. According to Guimarães et al. (2013), the activity of aluminum in solution is controlled by pH values, being low or null in values above 5.5. Studying Amazonian soils, Souza et al. (2018) found aluminum saturation values (m) above 50%. These results are common in Amazonian soils, due to the removal of the bases by leaching (Freitas et al., 2013).

Franciscon et al. (2019) also observed that P decreases with increasing depth in soils from natural environments in Amazonas. Freitas et al. (2013) attributed this situation to the availability of phosphorus due to the decomposition of organic matter with its low mobility in the soil and to the low contribution of ash deposition due to burning, in the case of low levels in pasture environments.

The higher content of organic C in the horizons of the surface is related to the greater entry of material and cycling in this location. In tropical environments, due to high temperatures and mineralization rates of organic matter, the stability of this material is low (Zenero et al., 2016). Generally, the organic matter content is less than 30 g kg^{-1} in the superficial horizons in most of the soils of the Amazon (Garcia et al., 2013). Conversion of native vegetation to pasture can lead to the accumulation of C in the soil or release CO_2 into the atmosphere, depending on the type of management applied to the soil and forage. In the condition of non-degraded pastures cultivated in highly fertile soils, there is a significant accumulation of C. However, in soils with low fertility, the implementation of pastures results in losses of C in the soil. However, the magnitude of the losses depends on the degree of degradation of the pastures (Carvalho et al., 2010).

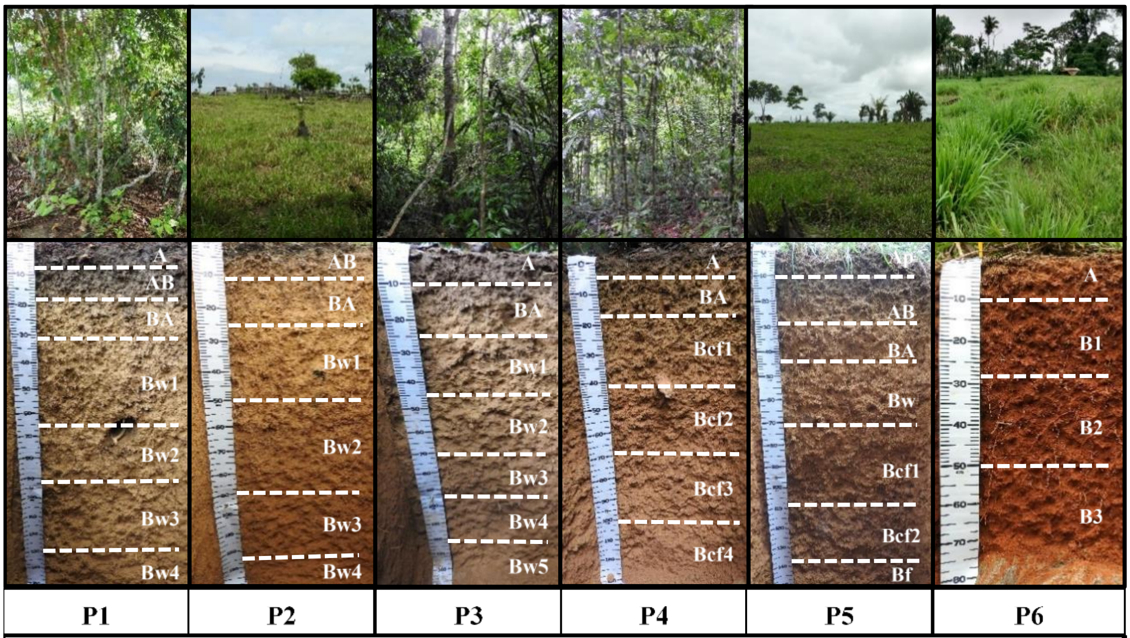
Soil classification

Based on the Brazilian Soil Classification System (Santos et al., 2018), the six profiles were classified up to the 4° categorical level, being used for the 5° level type A horizon and textural group. By the World Reference Base for Soil Resources (WRB) (WRB, 2015), the profiles were classified according to the key for the reference soil groups, the main qualifiers and the supplementary qualifiers (*Fig. 6*).

There were no variations in the superficial horizons, they only showed moderate A with thicknesses varying from 5 to 11 cm, except in P2 where there was a decrease in the thickness of horizon A due to the erosive process. This pattern is due to four factors, the replacement of native vegetation, the steeper relief, the high rainfall (Zenero et al., 2016) and the texture of the soil, composed mainly of sand-sized particles and composed of quartz, favoring less aggregate stabilization (Almajmaie et al., 2017). These factors contribute to a greater structural fragility, causing the removal of soil particles, not allowing the formation of a thicker A horizon and often intensifying the erosion process.

In relation to the taxonomy of soils, the profiles were classified under two main orders: Latossolos and Plintossolos, which varied only in the 2° and 4° categorical level for Latossolos, and in the 5° categorical level for Plintossolos. In general, the soils have low fertility and, therefore, were characterized as dystrophic. The Latossolos are associated with environments located in higher places, in areas whose relief varies from flat to smooth wavy, well drained, with a slope varying from 0.5 to 4.5%, these soils are deep with clayey texture. Plintossolos are related to lower relief environments, varying from smooth wavy to wavy, are moderately drained, with slopes ranging from 1.6 to 9.0%, and have a clayey to very clayey texture with more than 50% of coarse material where there is a predominance of petroplintite.

According to the WRB classification, the formation of two groups FERRALSOL (P1, P1, P3 and P6) and PLINTHOSOL (P4 and P5) were observed, presenting Haplic for FERRALSOL and Pisoplinthic for PLINTHOSOL as main qualifiers. Regarding the secondary qualifiers, Alumic and Clayic characteristics are observed for the profiles, except in P5 where it was qualified as Dystnic (*Fig. 6*).



P1 = LATOSSOLO AMARELO Distrófico típico, A moderado, textura argilosa
Haplic FERRALSOL (Alumic, Clayic)
P2 = LATOSSOLO AMARELO Distrófico típico, textura argilosa
Haplic FERRALSOL (Alumic, Clayic)
P3 = LATOSSOLO AMARELO Distrófico típico, A moderado, textura argilosa
Haplic FERRALSOL (Alumic, Clayic)
P4 = PLINTOSSOLO PÉTRICO Concrecionário êndico, A moderado, distrófico, textura muito argilosa
Pisoplinthic PLINTHOSOL (Alumic, Clayic)
P5 = PLINTOSSOLO PÉTRICO Concrecionário êndico, A moderado, distrófico, textura argilosa
Pisoplinthic PLINTHOSOL (Alumic, Clayic)
P6 = LATOSSOLO VERMELHO Distrófico cambissólico, A moderado, textura argilosa
Haplic FERRALSOL (Dystnic, Clayic)

Figure 6. *Images of the environments and profiles classified in a toposequence under sandstone/gneiss in the União Bandeirantes district, Porto Velho, RO*

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The relief as a conditioner for soil modifications did not generate enough variations to differ in the categorical levels for Latossolos, in which the observed change was only for the 2° and 4° categorical level in P6 due to the differences in the parent material, which changes from superficial formations to gneissic-migmatitic complex (Adamy, 2010). In Plintossolos, changes were observed only in the textural group.

Multivariate analysis

The formation of three groups by cluster analysis in the surface horizon (*Fig. 4A*), with GI and GII represented by P6 and P4, respectively, which formed independent groups, indicate that the chemical and physical attributes have a low value of similarity with the other profiles (Souza et al., 2018). The groups in the subsurface horizons (*Fig. 4B*) were formed due to the differences in the physical attributes of each sample fraction (ADFE and gravel) and granulometry (sand and clay) observed between the profiles. This pattern demonstrates that group analysis was important to distinguish soil orders. In the same sense, the observed pattern corroborates the studies by Campos et al. (2010), who used cluster analysis to distinguish geomorphic environments. Consistent results are also reported by Freitas et al. (2015) referring to changes in the chemical and physical attributes of the soil subjected to sugarcane, forests and reforestation, using dendrograms and other multivariate statistical techniques.

The values above average for Ca^{2+}, Mg^{2+}, pH in H_2O and in KCl observed in the second group (*Fig. 5A*) can be attributed to the use of fire to clean the areas, which leaves Ca^{2+} and Mg^{2+} ash through and increases the soil pH (Zenero et al., 2016). Studying soils under different uses in the Amazon, Pantoja et al. (2019) observed that soil acidity is the main limiting factor for crop development, requiring the adoption of corrective pH practices with improvements in nutrient supply. Likewise, group three characterized by the weight of acidity components is characteristic of this natural environment, and this behavior can be attributed to the deposition of organic matter on the soil surface by the forest (Morais et al., 2012). The decomposition of organic matter releases organic compounds on the soil surface, favoring the formation of water-soluble organic complexes, between Ca^{2+} and Mg^{2+} with organic ligands, facilitating the descent of these cations in the soil profile (Freitas et al., 2015), which causes acidification from soil. The formation of three groups in the subsurface horizons (*Fig. 5B*) is attributed to the parent material that is different in Yellow Oxisols and Petric Plinthosols (surface formations) for Red Oxisols (gneiss-migmatite complex) (Adamy, 2010).

Studying the multivariate analysis in the evaluation of soil attributes in areas with different uses in the region of Humaitá, Amazonas, Pantoja et al. (2019) concluded that the multivariate classification based on the physical and chemical attributes of the soil helps in the proper planning of land use and indicates which attributes are more sensitive for the studied environments.

Conclusions

Along the toposequence, two soil orders were observed, Latossolos and Plintossolos. The Latossolos occur in flat areas and are drained while the Plintossolos are located in environments close to the rivers in areas where the relief is more wavy, being moderately drained.

The studied soils were subjected to changes in surface horizons, granulometry, soil density, exchangeable bases and acidity components, and the profiles of the pasture areas had greater fertility in relation to the forest areas.

Through multivariate analysis for the diagnostic horizons, the formation of three groups of soils for the studied toposequence were found: the Latossolos Amarelos, which are quite weathered, with high levels of sand and exchangeable aluminum; the Plintossolos Pétricos, with high levels of gravel; and Latossolos Vermelhos, which are slightly more fertile soils, with a high capacity to exchange cations, pH and silt in relation to the others.

Conflict of interests. The authors declare that they have no conflict of interests.

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