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Artigo de Pesquisa

Variation of soil attributes along a sandstone-gneiss toposequence in southern Amazonas, Brazil

Atributos do solo e suas variações ao longo de uma topossequência arenito-gnaisse no sul do Amazonas, Brasil

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Abstract: Soil-landscape relationships in natural environments can provide helpful insights into soil suitability and limitations and necessary changes regarding agricultural land use and management. The objective of this work was to verify soil variations along a sandstone-gneiss lithological toposequence in the western Amazonian region of Brazil. Within this topolithosequence, the following soil profiles were sampled: *CAMBISSOLO HÁPLICO* (Dystric Leptic Cambisol), *NEOSSOLO REGOLÍTICO* (Cambic, Lithic, Leptosol), *NEOSSOLO QUARTZARÊNICO* (Dystric Regosol), *PLINTOSSOLO PÉTRICO* (Petric, Plinthosol), and *ARGISSOLO AMARELO* (Chromic, Abruptic, Acrisol). These profiles were located on the following slope segments: interfluve (P1), convex creep slope (P2), transportational midslope (P3), colluvial footslope (P4), and alluvial toeslope (P5). Soil analyses included physical and chemical attributes. The influence of the landscape on soil attributes was evaluated through randomness test, run charts, Pearson correlation, and Tukey test at a 5% significance level. Soil chemical properties were more sensitive to slope-related variations, with increased chemical quality in P2 for both horizons. Soil organic matter proved to be crucial for improving the chemical and physical quality of sandstone soils.

Keywords: Amazonian soils; Geomorphology; Landscape.

Resumo: Em ambientes naturais, a relação-solo paisagem pode ser útil no conhecimento da aptidão, limitação e mudança do uso da terra na região amazônica. Portanto, o estudo avaliou a influência da paisagem no comportamento físico-químico de solos em uma topolitossequência arenito-gnaisse no Sul do Amazonas. As amostras de solo foram coletadas em perfis de: Cambissolo Háplico, Neossolo Regolítico, Neossolo Quartzarênico, Plintossolo Pétrico e Argissolo Amarelo, abertos e descritos ao longo de uma topolitossequência arenito-gnaisse. Os perfis localizaram-se nos seguintes segmentos de vertente: (P1) topo, (P2) terço superior, (P3) terço inferior, (P4) sopé de transporte e (P5) sopé de deposição. Foram analisadas os atributos físicos e dos solos. A influência da paisagem nos atributos dos solos foram interpretas por análise de aleatoriedade, run charts, correlação de Pearson e teste Tukey 5% de probabilidade. Os solos apresentaram características marcantes do material arenítico e gnáissico o qual deram origem aos solos. As propriedades químicas foram mais sensíveis as variações dos segmentos de vertente, sendo o terço superior o que apresentou melhor qualidade química para ambos os horizontes. A matéria orgânica do solo mostrou-se peremptório para melhoria da qualidade química e física dos solos areníticos.

Palavras-chaves: Solos amazônicos; Geomorfologia; Paisagem.

1. Introduction

Amazonian environments are known worldwide for their diversity of fauna, flora, and mineral resources (MELO et al., 2017; GOMES et al., 2019). Relationships involving soil, relief, and vegetation characterize by being interdependent. According to Silva et al. (2018c), the terrain topography, as a determinant of soil formation and vegetation distribution, controls these associations. The topography determines variations in the hydric regime, favoring more or less developed soils, reflecting on a higher or lower capacity to support the vegetation. (HOFFMANN et al., 2018). However, population growth has triggered increased demand for food and space for house construction, promoting the anthropization of natural environments and causing changes in the characteristics of the ecosystems (SANTOS et al., 2019).

Variations in soil components are determined by pedogenetic factors but also by anthropic actions (JENNY, 1941; BOCKHEIM et al., 2005). The relief of the landscape acts as a decisive factor of the chemical and physical properties of the soil and the regional vegetation (MOMOLI; COOPER, 2016). Santos et al. (2013) concluded that edaphic characteristics, such as silt/clay ratio, V%, ki, and soil mineralogy, are subordinated to landscape variations. Therefore, evaluating the soil in the landscape context is fundamental to better differentiate natural environments in terms of use, suitability, and limitations, reducing the negative impacts imposed by the conversion of natural areas for human activities. In addition, the changes caused by the different positions raise the importance of the soil survey in the understanding of landscape variations (FERREIRA et al., 2018; SILVA et al., 2020).

Recognizing soil alterations caused by changes in land use is generally not an easy task (AQUINO et al., 2014; OLIVEIRA et al., 2015; GOMES et al., 2018). Therefore, variables related to soil structure are generally used in association with physical and chemical attributes as quality indicators. Conventional statistical methods, based only on the local average of soil attributes, hinder the correct interpretation of results when many variables are involved (FREITAS et al., 2018; OLIVEIRA et al., 2018). Using statistical process control such as run charts has helped differentiate environments when used as quality indicators to distinguish non-random or special causes resulting from process instabilities (SILVA et al., 2020).

Research conducted in the Amazon highlights its high biodiversity (MELO et al., 2017). However, Brazilian Amazonian soils tend to have poor fertility, with low levels of P, Ca^{2+}, and Mg^{2+}, and high acidity and Al^{3+} saturation (BRAZ; FERNANDES; ALLEONI, 2013). The deforestation of the Amazonian Forest is another aspect that deserves attention. It has exceeded national borders and gained global significance. The process of vegetation overturning and burning has been widely used as a practice in agricultural and livestock production systems, with significant impacts on the chemical properties of the soils (MULLER et al., 2001).

Given the extension of the Amazonian region, there is a current need for studies connecting soils and landscape expression (CAMPOS et al., 2011). Soil characteristics are indicators of the ecosystem dynamics, as they are intrinsic to origin-related factors, such as parent material and relief, which define its composition (MOTA et al., 2002). Soil chemical and physical attributes might be strongly determined by the relief, giving place to autochthonous or allochthonous characteristics or even mixed pedoenvironments. Such facts highlight the importance of recognizing the origin of soil properties to establish proper conservation measures that guarantee the protection of resources within the Amazonian biome.

A minimum knowledge of the soil is needed to understand its suitability, limitations, and dynamics and provide relevant information for the proper guidance of research regarding the alteration of natural environments (GONÇALVES, 2010). Soil variations in different topographic positions are crucial to comprehend ecosystem dynamics and the development of studies in natural Amazonian environments. Therefore, in the present study, soil-landscape relationships were considered to evaluate the physicochemical patterns of different soils in a sandstone-gneiss topolithosequence in the southern region of the Amazonas state, Brazil.

2. Materials and Methods

The study was conducted in the *Campos Amazônicos* National Park (PNCA - "*Parque Nacional dos Campos Amazônicos*", in Portuguese). The Park is located in the Municipality of Manicoré, AM, and extends along the *Estanho* highway (km 150), which connects to the Transamazonian Highway (BR 230) (Figures 1a–d). According to the Köppen classification, the climate is tropical wet (AM), with a short dry period and a rainy season from October to July. Temperature ranges from 25 to 27°C, and the average annual precipitation is 2,500 mm, with the relative humidity of the air varying from 80 to 90%. The soil is poorly developed, and the predominant parent material is sandstone-gneiss. The vegetation of the PNCA includes a mosaic of phytophysiognomies. Among these are ombrophilous and campinarana forests, cerrado, and savannas (PMPNCA, 2011).

Regarding its geology, the area belongs to the Basin of the *Alto Tapajós*, in the southern portion of the Amazonian Craton, covering the boundary between the geochronologic provinces *Tapajós-Parima* and *Rondônia-Juruena* (REIS et al., 2013). The deposition of the sandstone from the *Palmeiral* Formation in the continental environment occurred under a fluvial regime (DELLA-JUSTINA, 2009). Mineralogically, the sandstone is constituted by quartz. Although in smaller proportions, it also contains muscovite, biotite, adamellite, and granodiorites. These rocks have a cratogenic intrusive origin as stocks and batholiths (BAHIA, 1977; BRASIL, 1978). The gneisses of the *Nova Monte Verde* Complex are constituted of tonalitic to granitic orthogneisses, migmatites, and supracrustal rocks, such as garnet-biotite gneisses, sillimanite gneisses, calci-silicic rocks, and amphibolites (MADRUCCI; VENEZIANI; PARADELLA, 2003).

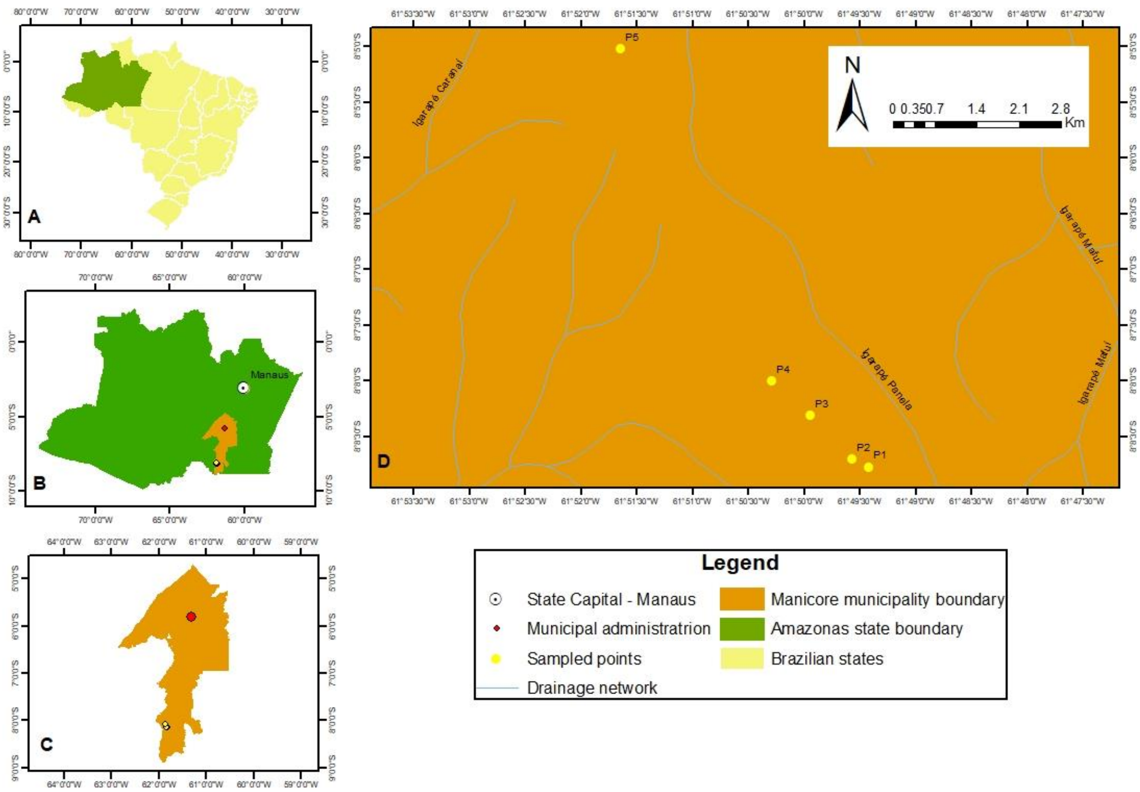


Figure 1. Topographic profile of the terrain: (a) Brazilian states (b) Amazonas state boundary, (c) Manicore municipality boundary, and (d) location of the soil trenches in a sandstone-gneiss topolithosequence in southern Amazonas, Manicoré, Amazonas, Brazil.

The topolithosequence extends for 9502 m following the spike of the slope in the direction of the gentler gradient. It starts at the top of the deposition foothill, with an altimetric profile ranging from 95 to 125 m (Figure 2). The establishment of the track followed a slope transect from the top to the toeslope (P5) towards the less angled dip direction (Figure 1 and 2). Altitude measurements were performed along the track and trenches opened in five segments of the topolithosequence: top or interfluve (P1), convex creep slope or upper third (P2), transportational midslope or lower third (P3), colluvial footslope (P4), and alluvial toeslope (P5) (DALRYMPLE et al., 1968).

Additionally, to confirm the mutual relationships between the physical environment and the genesis of the studied soils, field observations were conducted by a local pedologist and a geomorphologist.

Profiles 1 and 4 were at the top of the toposequence (P1) and the colluvial footslope (P4), respectively. In both cases, the relief was gently undulating, with a slope of 5 %. For profiles 2 and 3, located in the upper (P2) and lower thirds (P3), respectively, the relief was undulating, with a slope of 5 %. The topography of the alluvial toeslope (P5) was flat and extended within the gneiss rock domain (Figure 2). The sandstone-derived soils (P1, P2, P3, and P4) occupied an approximate extension of 4200 m, while those derived from gneiss (P5) extended for an area of 2902 m. Along the topolithosequence, the lithic contact of the geological substrates occupied an area of 2400 m, characterized by a mixture of soils with fragments of gneiss-sandstone. The segments of the topolithosequence had different types of vegetation. In P1 and P2, the vegetation was dense *cerrado*; in P3 and P4, it was low and high *cerrado*, respectively; and in P5 it was dense primary forest.

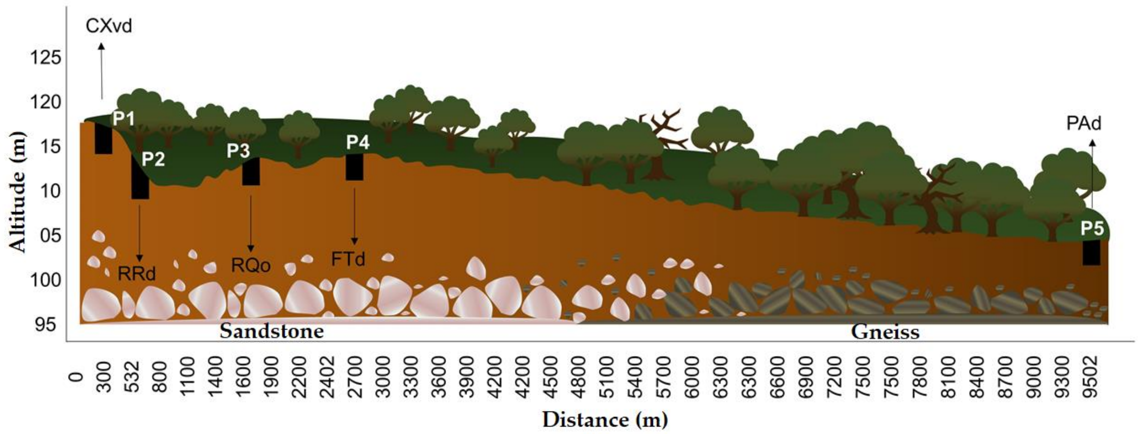


Figure 2. Topographic profile of the terrain and position of the trenches in a sandstone-gneiss topolithosequence in southern Amazonas, Manicoré, Amazonas, Brazil.

For the physical and chemical characterization of the soil, ten undisturbed and disturbed samples were collected from the lateral surface of each soil profile. Steel rings were used for the sampling within the surface and subsurface diagnostic horizons. The depths studied were 0 – 16 cm and 30 – 55 cm (P1), 0 – 10 cm and 10 – 20 cm (P2), 0 – 7 cm and 10 – 20 cm (P3), 0 – 18 cm, and 48 – 70 cm (P4), 0 – 18 cm and 49 – 74 cm (P5).

Following the Brazilian Soil Classification System (SANTOS et al., 2018), the soils were classified as *CAMBISSOLO HÁPLICO* (Dystric Leptic Cambisol [CXvd]), *NEOSSOLO REGOLÍTICO* (Cambic, Lithic, Leptosol [RRd]), *NEOSSOLO QUARTZARÊNICO* (Dystric Regosol [RQo]), *PLINTOSSOLO PÉTRICO* (Petric, Plinthosol [FTd]) and *ARGISOLO AMARELO* (Chromic, Abruptic, Acrisol [PAd]). Samples collected as soil lumps were air-dried in the shade, sieved on a 2 mm mesh, and used for physical and chemical analyses.

Bulk density (BD) was determined through the volumetric ring method (TEIXEIRA et al., 2017). The granulometric analysis was performed through the pipette method, using a 0.1-N NaOH solution as a chemical dispersant and high rotation mechanical agitation for 15 min. The clay fraction was separated through sedimentation, and both the fine and coarse sand fractions through sieving, while the silt fraction was determined by difference (Embrapa, 2011). Particle density (Dp) was measured through the volumetric flask method, and total porosity (TP) was calculated based on BD and Dp (TEIXEIRA et al., 2017).

Following the analytical procedures described by Teixeira et al. (2017), the following parameters were also determined: exchangeable calcium, magnesium, and aluminum, extracted with a 1-mol L^{-1} KCl solution; available phosphorus and potassium, extracted with Mehlich-1 solution; and potential acidity (H+Al), measured through extraction with a buffered calcium acetate solution at pH 7.0. The results of exchangeable cations and potential acidity were used to calculate cation exchange capacity (CEC), the sum of bases (SB), and base (V%) and aluminum (m%) saturations.

A potentiometer was used to measure the pH in the soil solution, using a 1:2.5 proportion of soil to water/KCl solution (EMBRAPA, 2011). Organic carbon (OC) was determined through wet oxidation with external heating (YEOMANS; BREMNER, 1988). Carbon stock (CS) was calculated using the expression: CS = (OC × BD × e) / 10, where: CS is the organic carbon stock in the soil (mg ha^{-1}), OC is the total organic carbon content (g kg^{-1}); BD is the bulk density (mg m^{-3}); and e is the soil layer thickness (cm) (COSTA et al., 2009a).

All data collected underwent descriptive statistical analyses followed by variance analysis. Whenever differences were found, a Tukey's test was performed at a 5% significance level to identify statistically significant differences. Clay fraction content of the diagnostic horizons was evaluated using statistical process control (DELLARETTI FILHO; DRUMOND, 1994). This analysis enabled a better understanding of the landscape influence under clay variation. The following classification was used (a) Cluster: when the set of points in the graph was either above or below the median; (b) Trend: successive increases and decreases in detected observations when the amount of successive helpful observations was higher than 7; (c) Mixture: absence of points near the central line, i.e., points positioned alternately above and below the central line (median), indicating data from two distinct populations; (d) Oscillation: indicates the existence or the absence of a pattern, which is seen when data fluctuates up and down, either above or below the median.

Data randomness was assessed through a 5% probability test. The non-random patterns indicate contrasts and similarities in soil profiles inside control limits (P1 – P5). Randomness tests were complemented by I-MR control charts, providing more accurate quality indicators. I-MR control charts (individual values and moving range) have central lines (overall average and range average) and upper (UCL) and lower (LCL) control limits. These two control limits are calculated based on the standard deviation of the clay content. The UCL is the mean value plus three times the standard deviation, and the LCL is the mean value minus three times the standard deviation when greater than zero. The statistical analyses were performed using the Minitab 16 software and followed equations 1, 2, and 3.

$$\times = \mu \quad (1)$$

$$UCL = \mu + 3\frac{\sigma}{c_2\sqrt{n}} \quad (2)$$

$$LCL = \mu + 3\frac{\sigma}{c_2\sqrt{n}} \quad (3)$$

In which,

× - central line; μ - mean of the means within a subset; UCL - upper control limit; σ - standard deviation; c2 - normal distribution correction factor, tabulated at n; n - sample size; and LCL - lower control limit.

A multivariate factor analysis of the main components was conducted using the STATISTICA® software (STATSOFT, 2004). This analysis indicates the sets of soil attributes that better discriminate the studied environments. It also determines the areas for which the attributes are influenced the most by the relief (REIS, 2001).

3. Results

The texture of the soils varied along the topolithosequence. It was loamy sand at the top (P1), upper (P2) and lower (P3) thirds, sandy loam at the colluvial footslope (P4), and clay at the alluvial toeslope (P5) (Table 1). Particle density (Dp) was not statistically different ($p < 0.05$) between slope sections, indicating absolute dependence on parent materials. Silt content within the superficial diagnostic horizon only differed at the interfluve section (P1). In the subsurface horizon, the lowest silt contents were not only for section P1 but also for the transportational midslope (P3). For sand and clay contents, a significant variation was detected along the slope within the sampled horizons. In the superficial horizon, clay and sand fractions were best represented in the colluvial footslope (P4) and the interfluve (P1), respectively. This pattern changed in the subsurface horizon, where the highest clay content corresponded to the colluvial footslope (P4) and the alluvial toeslope (P5) whereas, for the sand content, the highest levels were in the transportational midslope.

Soil position in the landscape influences pedogenetic processes and attributes (Ghidin et al., 2006; Silva et al., 2020). Therefore, considering that at the P5 section the clay content in the subsurface diagnostic horizon is twice as much as in the superficial horizon, it is possible to affirm that there is no genetic relationship between the soil and the underlying rock, suggesting an allochthonous origin. Section P5, positioned at the base of the slope, is formed by alluvial and colluvial soils originated from fragments of materials eroded from environments located at higher altitudes within the landscape.

Table 1. Physical attributes of the soil in a sandstone-gneiss topolithosequence in the southern region of Amazonas, Manicoré, Brazil.

Slope Sections	Sand	Silt	Clay	BD	Dp	TP
	-------------g kg^{-1}----------			------g cm^{-3}------		---%---
Superficial Diagnostic Horizon						
Interfluve	842 a	89 b	69 c	1.41 b	2.6 a	49 a
Convex creep slope	791 c	121 a	88 b	1.50 a	2.5 a	43 b
Transportational midslope	827 b	117 a	56 d	1.41 b	2.6 a	49 a
Colluvial footslope	643 d	124 a	233 a	1.38 b	2.6 a	48 a
Alluvial toeslope	755 c	146 a	99b	1.38 b	2.6 a	49 a
Subsurface Diagnostic Horizon						
Interfluve	809 b	95 b	96 b	1.45 a	2.5 a	43 b
Convex creep slope	800 c	116 a	84 b	1.50 a	2.6 a	40 c
Transportational midslope	841 a	95 b	64 c	1.50 a	2.7 a	46 a
Colluvial footslope	634 cd	128 a	238 a	1.46 a	2.5 a	44 b
Alluvial toeslope	234 d	218 a	548 a	1.51 a	2.7 a	41 c

BD = Bulk density; Dp = particle density; TP= total porosity; Mean values followed by the same letter do not differ by Tukey's test at 5% probability.

Within the surface diagnostic horizons, bulk density (BD) ranged from 1.38 to 1.50 g cm^{-3}. The highest BD value corresponded to the upper third (convex creep slope - P2), statistically different from the other slope sections. Regarding BD in the subsurface diagnostic horizons, no significant difference was verified between slope sections, with values ranging from 1.45 to 1.51 g cm^{-3}. In general, BD was higher in the subsurface diagnostic horizon when compared to the surface diagnostic horizon. Within the surface diagnostic horizons, total porosity (TP) ranged from 43 to 49%. The lowest values for this variable were verified at the upper third of the slope (convex creep slope), statistically differing from the other slope sections (Table 1). Within the subsurface horizons, PT was lower than in the surface horizons. It varied between 40 and 46% and had significant statistical differences between the slope sections. The lowest PT values were confirmed at the upper third (convex creep slope) and the alluvial toeslope, followed by the top (interfluve) and colluvial footslope segments.

Table 2 shows standard randomness values detected through run chart analyses considering the different soil profiles and depths evaluated. These included cluster, mixture, trend, and oscillation patterns. Significant results were exclusive of the cluster pattern of profile 4 within the 48 – 70 cm depth. The non-randomness patterns for profiles 1, 2, 3, and 5 reveal that the similarity in clay variation was given by the low clay content of these soils. Their sandstone origin might have influenced these results while determining clay variation and landscape relationships.

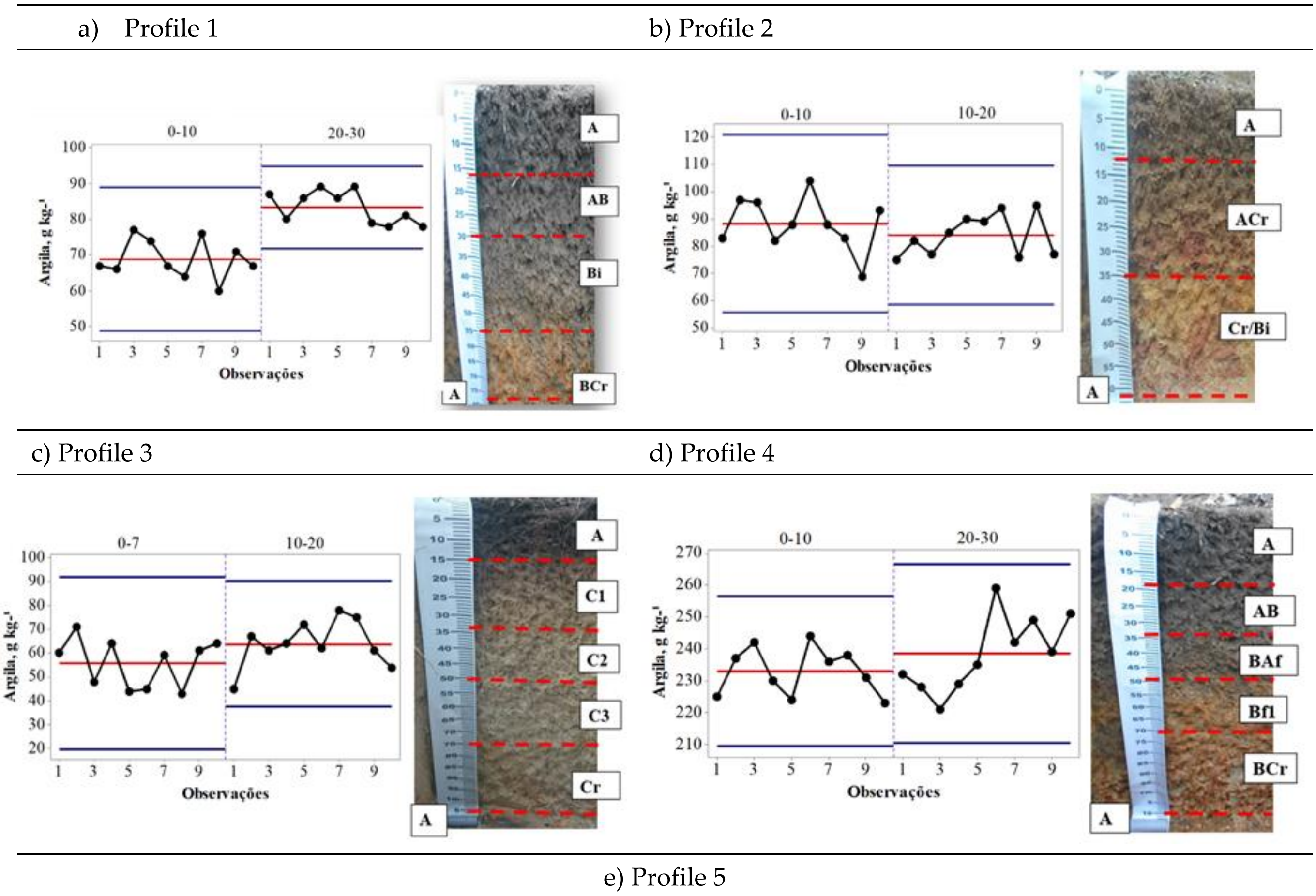
Table 2. Standard values of randomness in the characterization of the clay fraction in a sandstone-gneiss topolithosequence in the southern region of Amazonas, Manicoré, Brazil.

Indicators	Depht (cm)	Randomness patterns			
		Cluster	Mixture	Trend	Oscillation
Profile 1	0 – 16	0.800^{ns}	0.200^{ns}	0.710^{ns}	0.290^{ns}
	30 – 55	0.090^{ns}	0.910^{ns}	0.710^{ns}	0.290^{ns}
Profile 2	0 – 10	0.556^{ns}	0.444^{ns}	0.135^{ns}	0.865^{ns}
	10 – 20	0.251^{ns}	0.749^{ns}	0.916^{ns}	0.084^{ns}
Profile 3	0 – 7	0.251^{ns}	0.749^{ns}	0.710^{ns}	0.290^{ns}

	10 – 20	0.749^{ns}	0.251^{ns}	0.391^{ns}	0.609^{ns}
Profile 4	0 – 18	0.251^{ns}	0.749^{ns}	0.391^{ns}	0.609^{ns}
	48 – 70	0.004*	0.996^{ns}	0.391^{ns}	0.609^{ns}
Profile 5	0 – 18	0.749^{ns}	0.251^{ns}	0.391^{ns}	0.609^{ns}
	49 – 74	0.500^{ns}	0.500^{ns}	0.135^{ns}	0.865^{ns}

^{ns}standard values of randomness identified by the probability test, with $p > 0.05$, at the level of 5% probability; *standard values with non-randomness identified by the probability test obtaining $p < 0.05$, at the level of 5% probability.

However, the non-randomness of the cluster pattern of profile 4 at the 48 – 70 cm depth shows similar values, which can be related to the location of the profile at the colluvial footslope segment of the topolithosequence. Control charts were used to assess the effect of slope sections on the pedoindicator characteristics of the clay fraction (Figure 3a–e). According to the control graphs, clay content in the profiles was within the UCL and LCL but fluctuated around the average, indicating homogeneity in the sampled data set. All surface layer profiles presented variation in clay content, with greater (UCL) and lower values (LCL) within the limit, confirming that clay content and its variations are intrinsic to the natural conditions of the soil. The similarity between patterns can be explained by the fact that profiles are under the same geological conditions throughout the lithosequence.



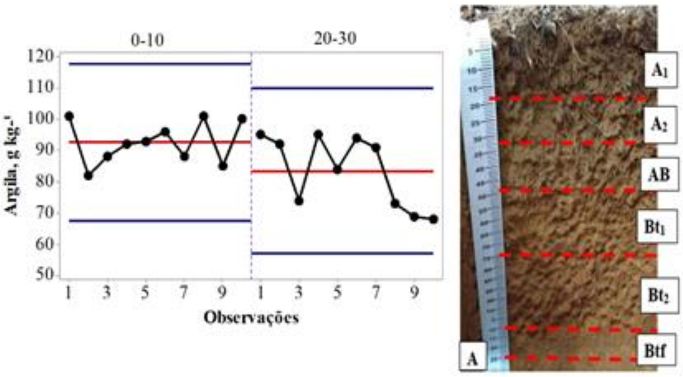


Figure 3. Clay fraction control charts with the vertical patterns used for the characterization of soil profiles using surface and subsurface diagnostic horizons in a sandstone-gneiss topolithosequence in southern Amazonas, Manicoré, Brazil. Profile 1: *CAMBISSOLO HÁPLICO* (Dystric Leptic Cambisol), Profile 2: *NEOSSOLO REGOLÍTICO* (Cambic, Lithic, Leptosol), Profile 3: *NEOSSOLO QUARTZARÊNICO* (Dystric Regosol), Profile 4: *PLINTOSSOLO PÉTRICO* (Petric, Plinthosol), Profile 5: *ARGISSOLO AMARELO* (Chromic, Abruptic, Acrisol).

As can be observed in the control charts, along the toposequence, clay contents were relatively low within the surface diagnostic horizons of the soil profiles. The exception was the colluvial footslope (P4), where the accumulation of clay was confirmed with an average clay content of 233 g kg^{-1}. Although clay contents within the subsurface diagnostic horizons were homogeneous and within the control limits, some increases were observed, indicating a typical case of the pedogenetic process of translocation. The highest clay contents were verified in the alluvial toeslope (P5), which can be explained by the occurrence of clay translocation to lower soil layers, a typical trait of *Argissolos* (Figure 3e).

Values for pH measured in water and KCl were similar among them and between the different slope sections. In general, the pH had an acidic character with a predominantly electropositive net charge in the soil solution (Table 3). Such interpretation is supported by the higher mean pH values at the interfluve and alluvial toeslope, independently of the horizon. The highest levels of Ca^{2+} occurred at the interfluve (P1), upper third (P2), lower third (P3), and colluvial footslope (P4). A significant difference was only found in the alluvial toeslope, where the lowest Ca^{2+} levels occurred. The contents of Mg^{2+} differed significantly between all slope segments, with the highest levels detected in the upper third (P2) and alluvial toeslope. Regarding K^{+}, it concentrated at the interfluve (P1) section, with a significant statistical difference between the diagnostic horizons.

Within the superficial diagnostic horizon, the sum of bases (SB) reached its highest value in the alluvial toeslope (P5), followed by the convex creep slope (P2). The SB was not statistically different within the other three slope sections, where it was significantly lower than at P5 and P2. In the subsurface diagnostic horizon, the highest SB values corresponded to the interfluve (P1) and the convex creep slope (P2), which significantly differed from the others slope sections. The base saturation (V%) ranged on average from 3 to 5% without significant variations along the slope nor between the diagnostic horizons (Table 3).

Soils can, therefore, be classified, as dystrophic and alic, given their superficial V% values and aluminum saturation (m%) below and above 50%, respectively. The highest Al^{3+} contents corresponded to the interfluve (P1) and the alluvial toeslope (P5), independently of the diagnostic horizon. The sandy texture of these soils and the occurrence of hydromorphism are possible explanations for the high values of Al^{3+} verified. When it comes to the acidic character of the soil, intense rainfalls and high contents of organic matter content are among the most probable reasons.

The results observed for CEC resemble those of the texture (Table 1). In the Alluvial toeslope, CEC followed the same pattern of the clay fraction. Indeed, CEC in tropical soils represents a clay characteristic, being considered an inorganic fraction of the soil. Therefore, CEC values varying from 17 cmolc dm^{-3} in the superficial horizon to 23 cmolc dm^{-3} in the subsurface suggested an allochthonous origin for the Pad. This way, the superficial soil of the profile did not inherit the chemical quality of the underlying rock, in this case, gneiss. The carbon content also confirmed these results. Although it was high at the superficial horizon, the organic matter content did not raise CEC in this horizon of the PAd.

Table 3. Chemical attributes in a sandstone-gneiss topolithosequence in the southern region of Amazonas.

Slope Segment	pH H_2O	pH KCl	Ca^{2+}	Mg^{2+}	K^+	SB	Al^{3+}	H+Al	CEC	V	m	P	OC	CS
			-----------------cmolc dm^{-3}	-----------------						%		mg dm^{-3}	g kg^{-1}	mg ha^{-1}
Superficial Diagnostic Horizon														
Interfluve	4.59 a	4.16 a	0.7 a	0.14 c	0.11 a	0.95 c	4.30 a	17.06 c	18 c	5 a	77 a	3 a	5.52 a	7.72 a
Convex creep slope	4.64 a	4.31 a	0.7 a	0.24 ab	0.05 b	0.99 b	1.39 b	22.02 ab	23 ab	4 a	58 b	3 a	4.51 b	5.92 b
Transportational midslope	4.62 a	4.12 a	0.6 a	0.15 c	0.04 b	0.79 c	2.57 b	20.71 b	21 b	4 a	76 a	2 a	4.43 b	4.39 c
Colluvial footslope	4.74 a	4.20 a	0.5 a	0.18 bc	0.05 b	0.73 c	2.85 b	24.06 a	25 a	3 a	80 a	3 a	5.18 a	6.58 b
Alluvial toeslope	4.43 a	4.08 a	0.18 b	0.26 a	0.04 b	0.48 a	4.30 a	16.62 c	17 c	3 a	78 a	4 a	5.26 a	7.31 a
Subsurface Diagnostic Horizon														
Interfluve	4.63 ab	4.01 a	0.4 b	0.09 ab	0.12 a	0.61 a	4,90 a	18.60 c	19 c	4ab	91 a	3 a	1.91 c	2.76 c
Convex creep slope	4.70 ab	4.08 a	0.8 a	0.17 ab	0.05 a	1.02 a	2,05 c	22.88 ab	24 ab	4 a	67 b	3 a	2.97 b	4.44 b
Transportational midslope	4.79 a	4.16 a	0.6 a	0.20 ab	0.05 a	0.85 b	2,64 b	21.50 bc	22 bc	4 a	76 a	2 a	2.34 c	3.04 c
Colluvial footslope	4.74 a	4.19 a	0.5 ab	0.09 b	0.04 a	0.35 b	3,43 ab	19.43 a	26 a	3 a	91 a	3 a	2.94 b	4.51 b
Alluvial toeslope	4.45 b	4.06 a	0.5 ab	0.23 a	0.06 a	0.79 b	4.20 a	21.72 b	23 ab	4 a	79 a	4 a	3.56 a	5.41 a

SB: sum of bases; CEC: cation exchange capacity; V: base saturation; m: saturation by aluminum; P: phosphorus; OC: Organic carbon; CS: carbon stock. Means followed by the same letter do not differ by Tukey's test at 5% probability.

These observations are in correspondence with the conditions of the area. In the colluvial footslope (P4), SB values below 0.7 cmolc dm^{-3}, m% higher than 80%, in addition to the contents of H^+ and Al^{3+} suggest saturation by acid cations. The soil content of available phosphorus was low (2 – 4 cmolc dm^{-3}), without significant statistical differences among the slope sections nor the soil horizons (Table 3). Mean values for this nutrient within the surface and subsurface diagnostic horizons indicate low P mobility in the soil, with some enrichment in the soil surface given by the litterfall of the native vegetation.

Within the superficial diagnostic horizon, the sum of bases (SB) reached its highest value in the alluvial toeslope (P5), followed by the convex creep slope (P2). The SB was not statistically different within the other three slope sections, where it was significantly lower than at P5 and P2. In the subsurface diagnostic horizon, the highest SB values corresponded to the interfluve (P1) and the convex creep slope (P2), which significantly differed from the others slope sections. The base saturation (V%) ranged on average from 3 to 5% without significant variations along the slope nor between the diagnostic horizons (Table 3).

Soils can, therefore, be classified, as dystrophic and alic, given their superficial V% values and aluminum saturation (m%) below and above 50%, respectively. The highest Al^{3+} contents corresponded to the interfluve (P1) and the alluvial toeslope (P5), independently of the diagnostic horizon. The sandy texture of these soils and the occurrence of hydromorphism are possible explanations for the high values of Al^{3+} verified. When it comes to the acidic character of the soil, intense rainfalls and high contents of organic matter content are among the most probable reasons.

The results observed for CEC resemble those of the texture (Table 1). In the Alluvial toeslope, CEC followed the same pattern of the clay fraction. Indeed, CEC in tropical soils represents a clay characteristic, being considered an inorganic fraction of the soil. Therefore, CEC values varying from 17 cmolc dm^{-3} in the superficial horizon to 23 cmolc dm^{-3} in the subsurface suggested an allochthonous origin for the Pad. This way, the superficial soil of the profile did not inherit the chemical quality of the underlying rock, in this case, gneiss. The carbon content also confirmed these results. Although it was high at the superficial horizon, the organic matter content did not raise CEC in this horizon of the PAd.

These observations are in correspondence with the conditions of the area. In the colluvial footslope (P4), SB values below 0.7 cmolc dm^{-3}, m% higher than 80%, in addition to the contents of H^+ and Al^{3+} suggest saturation by acid cations. The soil content of available phosphorus was low (2 – 4 cmolc dm^{-3}), without significant statistical differences among the slope sections nor the soil horizons (Table 3). Mean values for this nutrient within the surface and subsurface diagnostic horizons indicate low P mobility in the soil, with some enrichment in the soil surface given by the litterfall of the native vegetation.

Organic carbon (OC) and carbon stock (CS) were higher in the surface diagnostic horizon. Within this horizon, OC ranged from 4.43 to 5.50 g kg^{-1} and CS from 4.39 to 7.72 (Table 3), with a marked correlation between them. This increase in OC and CS in the soil surface layer might be related to the litter deposition on the topsoil and the increased root density, forming an organic matter layer.

In summary, these results show that chemical attributes were more influenced in the upper topolithosequence segments. The upper third (P2) presented better chemical quality for both surface and subsurface horizons as confirmed by the high soil levels of SB, CEC, and OC and the low m%.

Pearson's correlation coefficients (*r*) for soil attributes are presented in Figure 4. Positive correlations were verified between clay and Pt, pH, H+Al, Al^{3+}, SB, CEC, m%, P, OC, and CS. According to previous research, clay and soil organic matter (SOM) affinity results in the genesis of organomineral aggregates, explaining the correlation between clay and OC in sandy soils, improving soil chemical attributes (GOMES et al., 2018). Furthermore, previous findings have also confirmed a contribution between 30 and 40% of the organic matter to CEC in sandy soils (RAIJ et al.,1969).

A positive correlation between clay and OC was expected, given the dependence on clay for the genesis of stable aggregates of soil organic matter (GOMES et al., 2018). Clay keeps organic compounds protected from microbial degradation and solar irradiation. A positive and significant correlation between clay and Al^{3+} ($r = 0.50$; $p < 0.05$), H+Al ($r = 0.50$; $p < 0.05$) is related to an acidic condition, low CEC, and low clay activity, which corresponds with previous reports in the same region of study (BRITO et al., 2014). The presence of iron (hematite, goethite, maghemite) and aluminum (gibbsite) oxides within the clay fraction of Amazonian soils (OLIVEIRA, 2017) causes P fixation. It, therefore, explains this correlation with the clay fraction, even though weak and not significant ($r = 0.14$; p = ns).

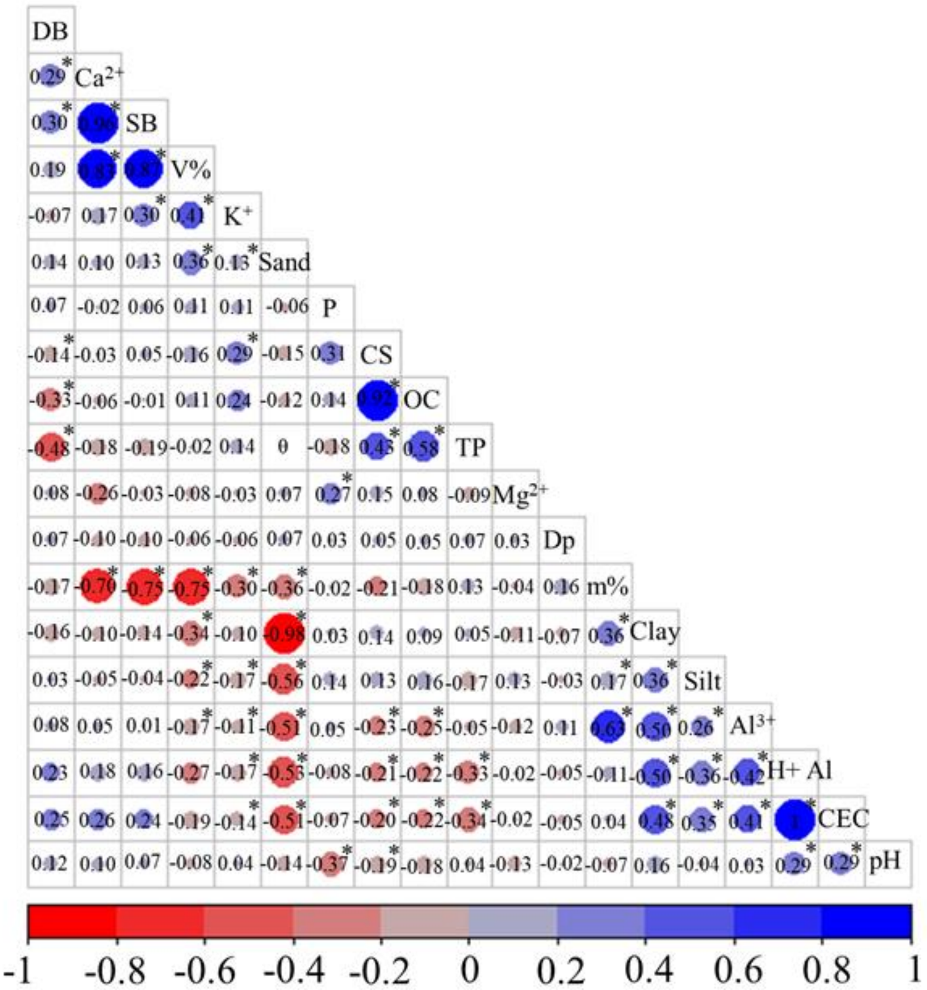


Figure 4. Correlation between clay in air-dried fine soil (ADFS) and soil attributes in a sandstone-gneiss topolithosequence in southern Amazonas, Brazil. BD = Bulk density; PT = total porosity; Dp = particle density; SB = sum of bases; CEC = cation exchange capacity; V% = base saturation; m% = aluminum saturation; P = phosphorus; CO = organic carbon; EC = carbon stock. * indicates the correlation is significant at the 0.05 level.

A negative correlation was verified between clay and BD (Figure 4). These relationships may partly be explained by the contribution of SOM, as suggested by the positive and significant correlation between clay and OC that improved soil physical quality. In addition, the correlation between CS and Pt (r= 0.44; p< 0.05) and OC (r= 0.92; p< 0.05) supports these finding. Therefore, soil organic matter was the main cause of soil chemical and physical quality, regardless of the landscape section. Given the low natural fertility of the soils in the region, it is essential to maintain soil organic matter to enable the agricultural use of the land.

As a premise for the principal component analysis (PCA), a Kaiser-Meyer-Olkin coefficient (KMO) of 0.85 was considered acceptable to generate the PCA graph (Table 4 and Figure 5). According to the variance values, which express the degree of dispersion regarding the expected value, potential acidity, CEC, and SB presented the highest dispersion and contributed the most to the total variance (Table 4).

Table 4. Correlation between principal components and soil attributes.

Attributes	[1]PC1	[2]PC2
Sand	-0.78*	0.41
Silt	0.50*	-0.35
Clay	0.76*	-0.39

TP	0.07	-0.29
BD	-0.02	0.69*
Dp	0.05	-0.26
pH (KCl)	0.38	-0.60*
Al^{3+}	0.60*	-0.44
Ca^{2+}	0.13	-0.86*
Mg^{2+}	-0.28	-0.75*
K^{+}	-0.35	0.19
P	-0.38	-0.71*
$H^{+}+Al^{3+}$	0,07	0.91*
OC	-0.07	-0.63*
CS	-0.16	-0.65*
SB	0.05	0.82*
CEC	-0.90*	0.14
Explained variance (%)	21.12%	43.50%

TP: total porosity; BD: bulk density; Dp: particle density; OC: organic carbon; CS: carbon stock; SB: sum of bases; CEC: cation exchange capacity; PC1: principal component 1; PC2: principal component 2.

Looking forward to differentiating the areas based on selected variables, a PCA was conducted (Figure 5). The first two PC explained 43.49% (PC 1 + PC 2 = 68.61%) of the variance related to the studied attributes in the superficial horizon and 25.12% in the subsurface one. In the PCA graph, it is possible to observe the relationship of the soil attributes with each slope section (Figure 5). The colluvial footslope was mainly related to the finer soil particles (silt and clay), directly influencing the higher CEC relationship with this slope section since fine soil textures favor CEC.

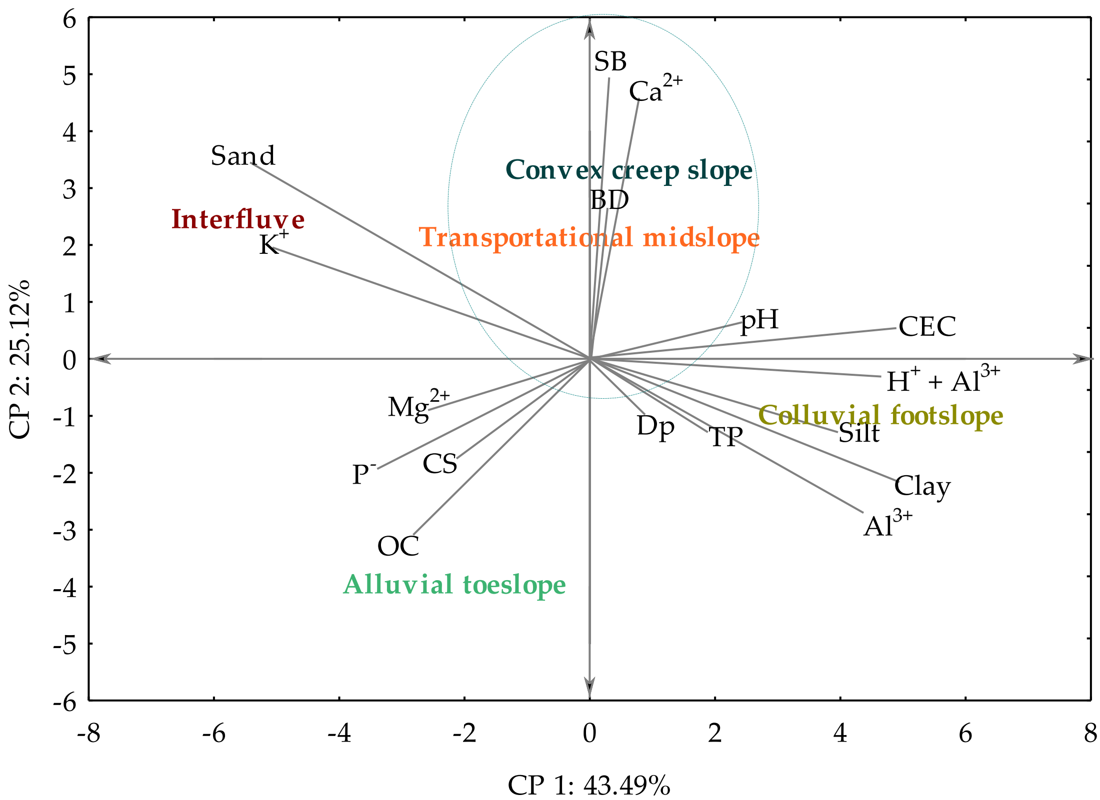


Figure 5. Principal component analysis of soil attributes in different relief positions within a sandstone-gneiss topolithosequence in the southern region of Amazonas, Brazil. PC1: principal component 1; PC2: principal component 2. TP: total porosity; BD: bulk density; Dp: particle density; OC: organic carbon; CS: carbon stock; SB: sum of bases; CEC: cation exchange capacity.

4. Discussion

The sand fraction predominated in both the surface and subsurface horizons, confirming the determinant character of the parent material for particle size, as previously suggested by research conducted in sandstone-gneiss soils (REIS et al., 2013; BRITO FILHO et al., 2018). The clay fraction decreased towards the lower third (P3), with significant differences compared to other slope sections. This reduction in the clay content in P3 might be associated with the organic matter displacement to the lower segments. Previous studies indicate the occurrence of eluviation as the principal explanation for clay translocation along a toposequence (FACCO et al., 2016). Thus, translocation and occasional erosive processes might explain the higher clay content verified at the colluvial footslope and the alluvial toeslope.

Landscapes intensify the variability of soil attributes by creating specific formation environments and affecting water distribution and the transportation of soil solids through the soil solution (LEPSCH; BUOL; DANIELS, 1977; KRASILNIKOV et al., 2005; SILVA et al., 2018c). In general, the BD values verified in the studied area are typical of sandy soils (MELO; ALEONI, 2009) with low clay content (FREITAS et al., 2014) and marked influence of the high quartz Dp which is 2.65 g cm^{-3} (PEREIRA et al., 2019). Given the sandy texture of the studied soils, BD values cannot be considered a limiting factor. In sandy soils, only when higher than 1.75 g cm^{-3}, BD becomes limiting for plant root growth (REICHERT et al., 2003; REINERT et al., 2008).

The similar BD values verified among the surface and subsurface horizons may be related to the soil parent material, given the abundance of quartz and the typical organization of sand particles, corresponding with the results reported by CAMPOS et al. (2012c) for sandy soils. None of the sections had porosity values below 10%, which is the critical value for proper root development (GRABLE; SIEMER, 1968). Additionally, the low Pt values might be explained by the sandstone and gneiss rocks of the local landscape, suggesting, as well, incipient pedogenesis. According to Gomes et al. (2019), sandy soils originated from sandstone rocks are dominated by sand fractions, and therefore have lower Pt values.

Total porosity can be related to BD (PANTOJA et al., 2019). Higher BD values are generally associated with lower Pt, confirming their inversely proportional relation. Similar results have been found in previous studies, in which a reduction in total porosity was related to an increase in BD (GOMES et al., 2017; 2018; CARMO et al., 2018).

Additionally, soil compaction has been related to reductions in total porosity, as it causes reduced infiltration capacity and increased erosive processes (VASCONCELOS et al., 2014). Furthermore, according to Condé et al. (2016), a rejected null hypothesis and positive z values indicate an aggregate distribution of the data. Environmental factors such as the soil and the landscape type rather than random processes influence this result.

Soil location in the topolithosequence caused clay accumulation as a consequence of erosion. Several studies have established that variations in landscape tend to favor relative gains and losses in clay content due to translocation, accumulating displaced clay from upper slope segments in lower ones, especially in sandy soils (CAMPOS et al., 2011; MOMOLI; COOPER, 2016; RODRIGUES et al., 2018; SILVA et al., 2020; BARRETO et al., 2019). This fact was reinforced by the occurrence of the transitional horizons AB and BA with a rich presence of Fe oxides in the clay fraction, giving yellow and red colors to the BAf and Bf1 horizons (Figure 2d). The presence of Fe oxides was also confirmed within the BCr horizon giving place to red mottling and ferruginous concretions defined as plintite. This phenomenon represents specific soil formation processes described as plintization and lateralization (SANTOS et al., 2018). The reduced Fe oxides (Fe^{2+}) translocated from the A, AB, BA, and Bf horizons precipitated in the BCr horizon in the form of oxidated iron (F3+). Eventually, consecutive wetting and drying cycles resulted in the hardening (cementation) of the iron oxides giving place to ferruginous nodulations, which are the main diagnostic character of *Plintossolos*.

The presence of a B textural diagnostic horizon (Bt) was confirmed in section P5, indicating deep clay accumulation given by the mobilization and loss of clay from the soil surface. Contrary to the other soils, the *Argissolo* had a uniform yellow coloration throughout the profile. According to Silva et al. (2020), the yellow color indicates the predominance of goethite, which is the principal Fe oxide in soils with low content of total Fe, such as those formed from sandstone and gneiss. The alluvial toeslope favors a more intense hydric activity, lower temperatures (P5 is located at the height of 105 m), and increased organic matter. All of these are edaphic environmental conditions that favor goethite formation (CURI; FRANZMEIER, 1984; SCHWERTMANN; TAYLOR, 1989; CORNELL; SCHWERTMANN, 2003), stimulating this process in the studied *Argissolo*. It is worth noting that this is the predominant specific soil formation process occurring within the *ARGISSOLO AMARELO* included in the present study.

Regarding chemical attributes (Table 3), previous research has already indicated the occurrence of acidic soils in the region, reflecting the acidic nature of sandstone and the low content of basic ions (CAMPOS et al., 2007). Results similar to the ones here observed for the SB (SILVA et al., 2013) and the influence of sandstone in soil pH were also reported in the Aquidauana geological formation (SCHIAVO et al., 2010). In addition, other factors also contribute to the increased soil acidity, including high temperatures and precipitation rates, which are typical of the Amazonian region (REIS et al., 2009; MEDINA et al., 2018), as well as SOM content. These two cause the excessive loss of bases by leaching, therefore, concentrating H^+ ions in the soil. The abundance of SOM, on the other hand, contributes to lowering pH through its carboxylic and phenolic functional groups that release H^+ (FREITAS et al., 2015).

The significant differences detected for CEC allowed a better comprehension of the relief and vegetation effect under the same parent material (Table 3). Within the superficial and subsurface horizons, lower CEC values were verified (17 cmolc dm-3), confirming the natural condition of the CXvc (P1) imposed by the parent material, in this case, sandstone. Given the effect of the vegetation on CEC, it does not enhance the CSvd chemical quality. This interpretation is possible given that the vegetation at P1, classified as dense cerrado, was the same as in the Convex creep slope. Therefore, under the same conditions of parent material and vegetation, at the RRd profile of the Convex creep slope (P2), CEC increased 22% compared to P1. Consequently, the relief was the determinant factor of the chemical quality of the soil, possibly because the RRd, located at the Convex creep slope, acting as a site of nutrient accumulation coming from the higher sections of the landscape, and particularly from the Interfluve (P1), through erosive processes.

Potential acidity (H+Al) was high (Table 3), corroborating results from previous studies (CAMPOS et al., 2012b). In contrast, soil CEC was low due to the low natural fertility and elevated acidity of the soils, which are characteristic of Amazonian environments (CAMPOS et al., 2012b). As previously demonstrated, an increase in the CEC does not always represent an improvement in the soil chemical quality since SB below 0.9 cmolc dm^{-3}, and m% above 80% may cause the saturation of negative charges by acidic cations, thus increasing soil buffer capacity (ALMEIDA et al., 2018).

Reduced pH values and Fe contents have been linked to intense P fixation in soil from the northern region of Brazil, caused by a reduction in its mobility in the soil solution (PIMENTEL et al., 2020). Phosphorus mobility was determined by soil organic matter and pH in quartzarenic soils in a toposequence, with higher P levels in the top (P1) and the toeslope (SOUZA et al., 2015). These results corroborated the one obtained in the present research.

Concerning the soil content of OC (Table 3), the levels found in the present study correspond with those previously reported for soil from the Amazonas (GOMES et al., 2017; 2018) and Cerrado, while studying organic carbon and humic fractions (NANZER et al., 2019). As suggested by CAMPOS et al. (2016), plant litter is the principal source of OC in Amazonian environments, leading to the chemical restoration of sandy soils. In a similar study, the highest levels of exchangeable cations were in the upper third (P2) (BALIEIRO et al., 2008). Therefore, increasing SOM content to induce higher CEC and SB levels would be especially relevant to the Amazon region and its typically acidic soils (PANTOJA et al., 2019).

A positive correlation was found between SOM and clay, OC, CS, and Pt (Figure 4). On the contrary, a negative correlation was found with BD. Previous findings supported these results, as they demonstrated that SOM serves as a buffer against losses in soil quality (VASCONCELOS et al., 2014; GOMES et al., 2019) while reducing the impact of external compaction forces and maintaining Pt (KRAVCHENKO et al., 2019; CORTEZ et al., 2020). These are crucial features in sandy soils, owing to difficulties in the formation of stable soil aggregates.

As shown in the PCA (Figure 5), at the top of the slope (interfluve), there is a strong relationship with sand, justified by its location in the highest part of the relief and the intense Amazonian hydric regime. During soil washing, the finer particles are taken by the water as part of the eluviation process (FEITOSA et al., 2016). Higher concentrations of finer particles in the lower parts of the terrain confirm this phenomenon. Schiavo et al. (2010), while studying a toposequence, identified higher values of sand in the upper part associated with increased levels of silt and clay in the lower sections.

Higher contents of OC, P, and Mg were observed at deposition foothill (alluvial toeslope). The lower part of the land was characterized by a more defined forest, with greater quantity and diversity of material, as well as material brought from the top of the land, which ends up favoring the increase of OC, and therefore, increased CS compared to the sections with less vegetation (ROSSET; SCHIAVO; ATANÁZIO, 2014). These might have contributed to the accumulation of Mg in this environment since carbon directly favors CEC (COSTA et al., 2015). Various studies found that greater CEC is associated with greater soil organic matter contents, due to a higher degree of oxidation of SOM and a higher surface area for cation adsorption sites (LIANG et al., 2006; SILVA et al., 2016; 2018a).

The transition between the upper and lower (Convex creep slope, and Transportational midslope) thirds was not clear. These two areas presented a high degree of proximity regarding attributes such as SB, BD, Dp, TP and Ca^{2+} content. Considering that these two sections had the highest SB, a few leaching problems might be associated with these environments, which, in turn, might be less influenced by the topography. It is possible to conclude that the higher nutrient availability may be directly related to the parent material (CHAGAS et al., 2013). Previous studies conducted in sandstone soils verified higher values of SB in the upper and lower thirds of the toposequence (SCHIAVO et al., 2010) and at the top of the slope (MAFRA et al., 2001).

Finally, the pedoenvironmental conditions of the colluvial footslope were best defined by the attributes silt, clay, and Al^{3+}. The colluvial footslope had the highest silt content, even when compared to other slope segments that shared gneiss as the parent material. As mentioned by Resende et al. (1999), the silt fraction indicates soil weathering or potential for easily weathered primary minerals, i.e., nutrient supply. As a possible explanation, Rosolen and Herpin (2008) concluded that lower positions and land depressions favor fine sediment deposition, given that finer particles are more easily carried. Furthermore, the PCA result indicated the relief as a relevant pedogenetic factor determinant of soil characteristics, even when originating from the same parent material.

5. Conclusions

The sandstone-gneiss nature of the parent material prevailed in the soils. The landscape had no determining effect on particle density distribution nor exchangeable phosphorus. Chemical properties were more sensitive to variations in landscape segments, with the upper third (P2) having the best chemical quality for both horizons. Soil organic matter proved to be essential for improving the chemical and physical quality of sandy soils. From the aspect of soil chemical and physical quality, landscape-related variations should not be limiting factors for the agricultural use of the land, independently of the slope section.

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