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Physical-hydric attributes in areas under forest-pasture conversion in southern Amazon, Brazil

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Description of the subject. The increasing occupation and exploitation of the Amazon has resulted in the increased conversion of forest areas into agricultural land or pasture. This often has negative impacts on soil and water dynamics. Therefore, there is a need for comparative studies between forest areas and those undergoing pasture conversion, in order to provide information to mitigate the impacts caused.
Objectives. This study aimed to evaluate the physical and hydrological attributes of areas where forest has been replaced by pasture, located in the southern Amazon, Brazil.
Method. The study areas are located in Humaitá, in the southern Amazon. For this study, five pasture areas, one natural pasture area, and one forest area were selected. A transect was established in each area containing fifteen sampling points. Mini trenches were opened at each point to collect soil samples (disturbed and undisturbed) in the 0.00-0.10 and 0.10-0.20 m depth. The samples collected in clods were dried in the shade and then crushed to obtain fine air dried soil. The volumetric rings (undisturbed samples) were saturated on the tension table and finally subjected to a penetrograph. Soil attributes such as sand, silt, clay, macroporosity, microporosity, total porosity, volumetric soil water content, and soil penetration resistance were also determined in the laboratory. The data obtained was tabulated and analyzed using descriptive statistics, a test of means to group the different environments, correlation analysis, and principal component analysis using multivariate analysis.
Results. The results indicate that the conversion from forest to pasture harmed soil penetration resistance, volumetric soil water content, total porosity, and soil macroporosity. Pearson correlation in the first depth (0.00-0.10 m) revealed that sand content negatively correlated with microporosity, total porosity, and silt but no correlation with the other attributes. The soil penetration resistance showed a negative correlation with macroporosity, total porosity, and volumetric soil water content, suggesting a direct relationship where changes in the volumes of macroporosity, total porosity, and volumetric soil water content can significantly affect the soil penetration resistance. In the 0.10-0.20 m depth, the soil penetration resistance correlated negatively with macroporosity and positively with microporosity. The total porosity, correlated positively with microporosity and macroporosity and negatively with sand content. In this depth, macroporosity showed no correlation with microporosity.
Conclusions. The forest and natural grassland areas stood out for having higher volumetric soil water content, microporosity, and total porosity, while the pasture areas were characterized by high penetration resistance.
Keywords. Soil, environmental impact assessment, soil quality, Amazonia.

Attributs physico-hydriques dans les zones en conversion forêt-pâturage du sud de l'Amazonie, Brésil

Description du sujet. L'occupation et l'exploitation croissantes de l'Amazonie ont entraîné une conversion accrue des zones forestières en terres agricoles ou en pâturages. Cela a souvent des effets négatifs sur la dynamique des sols et de l'eau. Il est donc nécessaire de réaliser des études comparatives entre les zones forestières et celles qui sont en cours de conversion en pâturages, afin de fournir des informations permettant d'atténuer les impacts causés.

Objectifs. Cette étude vise à évaluer les attributs physiques et hydrologique des zones où la forêt a été remplacée par des pâturages, situées dans le sud de l'Amazonie, au Brésil.

Méthode. Les zones d'étude sont situées à Humaitá, dans le sud de l'Amazonie. Pour cette étude, cinq zones de pâturage, une zone de pâturage naturelle et une zone forestière ont été sélectionnées. Un transect a été établi dans chaque zone contenant quinze points d'échantillonnage. Des mini-tranchées ont été ouvertes à chaque point pour collecter des échantillons de sol (perturbés et non perturbés) dans les couches 0,00-0,10 et 0,10-0,20 m. Les échantillons collectés en mottes ont été séchés à l'ombre puis broyés pour obtenir une terre fine séchée à l'air. Les anneaux volumétriques (échantillons non remaniés) ont été saturés sur la table de tension et finalement soumis à un pénétrographe. Les attributs du sol tels que le sable, le limon, l'argile, la macroporosité, la microporosité, la porosité totale, la teneur volumétrique en eau du sol et la résistance à la pénétration du sol ont également été déterminés en laboratoire. Les données obtenues ont été tabulées et analysées à l'aide de statistiques descriptives, d'un test de moyennes pour regrouper les différents environnements, d'une analyse de corrélation et d'une analyse en composantes principales par analyse multivariée.

Résultats. Les résultats indiquent que la conversion de la forêt en pâturage a nui à la résistance à la pénétration du sol, à la teneur volumétrique en eau du sol, à la porosité totale et à la macroporosité du sol. La corrélation de Pearson à la première profondeur (0,00-0,10 m) a révélé que la teneur en sable était corrélée négativement avec la microporosité, la porosité totale et le limon, mais pas avec les autres attributs. La résistance de pénétration du sol a montré une corrélation négative avec la macroporosité, la porosité totale et la teneur volumique en eau du sol, suggérant une relation directe où les changements dans les volumes de la macroporosité, la porosité totale et la teneur volumique en eau du sol peuvent affecter de manière significative la résistance de pénétration du sol. À la profondeur de 0,10-0,20 m, la résistance de pénétration du sol était corrélée négativement avec la macroporosité et positivement avec la microporosité. La porosité totale était corrélée positivement avec la microporosité et la macroporosité et négativement avec la teneur en sable. À cette profondeur, la macroporosité n'a montré aucune corrélation avec la microporosité.

Conclusions. Les zones de forêt et de prairies naturelles se distinguaient par leur teneur volumétrique en eau, leur microporosité et leur porosité totale plus élevées, tandis que les zones de pâturage étaient caractérisées par une résistance élevée à la pénétration.

Mots-clés. Sol, impact sur l'environnement, qualité du sol, Amazonie.

1. INTRODUCTION

Livestock farming in the northern region Amazon is associated with the extensive use of vast areas destined for pasture as the main food source in cattle farming. This region is home to one of the largest commercial cattle herds in the world, accounting for around 39,619 million cattle, playing a significant role in the country economy, contributing 20.17% of national production, according to data from Abiec (2022).

The conversion of natural forest environments into agroecosystems, agricultural, and livestock systems has led to significant changes in the soil physical, chemical, and biological attributes (Souza et al., 2020). These transformations can negatively impact the soil, depending on the management and type of use employed. Concerning the harm caused to pasture areas in the Amazon, the systematic use of stocking rates that exceed the regeneration capacity of pastures stands out (Lima et al., 2022a). In addition, according to Lima et al. (2022b), animal trampling has been one of the main causes of soil degradation processes, limiting the productive potential of the pasture for longer periods.

One of the main indicators of degradation in the productive capacity of pastures is soil structure. When this structure is negatively impacted, the rearrangement and/or reaccommodation of particles and/or aggregates occurs, causing compaction (Souza et al., 2020). In this context, attributes such as soil density, porosity, soil penetration resistance, and water infiltration are affected and can be used as indicators of the soil's physical and water quality (Sena et al., 2021). Authors such as Lima et al. (2022a) also point out that compaction tends to reduce the aeration, infiltration rate, and hydraulic conductivity of the soil, impacting surface runoff and consequently increasing the loss of water, soil, and nutrients. This set of negative effects can jeopardize the sustainability and productivity of areas destined for cattle ranching in the Amazon region (Lima et al. 2024).

In this sense, several studies have recorded the phenomenon of soil compaction in agricultural use systems in the Amazon, such as Jordão et al. (2021) and Silva et al. (2022), who highlight this phenomenon in comparative studies of natural areas and different crop systems in the southern Amazonas. On the other hand, Biazatti et al. (2022) and Lima et al. (2021) verified the influence of compaction on root growth in agricultural systems in the Amazon. Finally, Lima et al. (2022a), studying soil physical attributes in areas under pasture systems with *Brachiaria* and Mombasa grasses, found significant changes in soil attributes in northern Rondônia.

Despite these studies (Zárate-Salazar et al., 2024) and due to the vast extension of the Amazon region that allows for several classes of soils, research is needed to assess the impacts caused on the physical and water attributes of the soil caused by the conversion of natural environments into pastures. Considering that part of the region is covered by this type of vegetation, coupled with the continued advance of the agricultural frontier in the area, it is crucial to conduct research into this subject. Given this scenario, studies must compare the impacts of converting forests into pasture areas on the soil's physical and water attributes. The main hypothesis of this research was that pasture use systems altered soil attributes in different areas under conversion from forest to pasture in southern Amazon.

2. MATERIALS AND METHODS

2.1. Characterization of the study environments

The study areas are located in the state of Amazonas, in the Western Amazon region, more precisely in the southern part of the state, known as the "arc of deforestation" (**Figure 1**). This area was selected based on criteria that considered the presence of degraded pastures and areas of natural pasture and forest. In total, seven different areas were selected: four areas of rotational grazing, one area of extensive grazing, one area of natural pasture, and one area of forest (considered as a reference/control) (**Table 1**).

According to the Köppen classification, the climate of the region belongs to group A (Rainy Tropical Climate) and climate Am-type (monsoon-type rainfall), with a short dry season from June to September. Annual rainfall ranges from 2,500 to 2,800 mm. Annual temperatures range from 24 to 26 °C. Relative air humidity is considered high, ranging from 85% to 90% in the rainy season and between 60 and 70% in the dry season. The local relief is gently undulating, with altitudes ranging from 100 to 200 m (Alvares et al., 2013). The soil of the study area is classified as Latossolo Vermelho Amarelo, following the criteria established by the Brazilian Soil Classification System (Santos et al., 2018), and Ochric, Hyperdystric, Clayic, Chromic, Abruptic, Acrisol following the criteria established by the World Reference Base of Soils (IUSS Working Group WRB, 2022). It lies on the Amazon plain between the Purus and Madeira rivers. This area is associated with deposits of recent alluvial sediments from the Quaternary period. The soils have limited or deficient natural drainage.

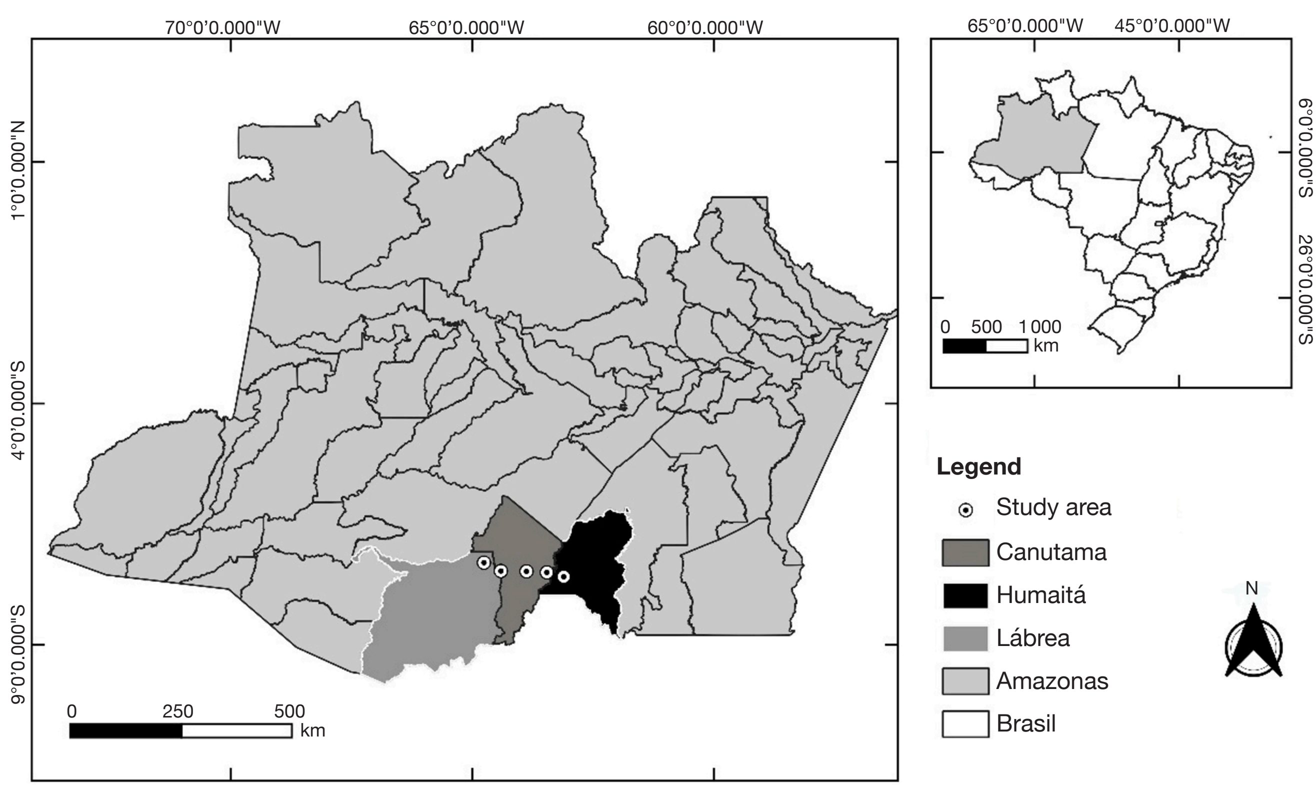

Figure 1. Map of the location of the study area — *Carte de l'emplacement de la zone d'étude*.

Table 1. Description of use and history of the areas under pasture and forest in the southern Amazonas — *Description de l'utilisation et historique des zones sous pâturage et forêt dans le sud de l'Amazonas*.

Study area	Description of the area
Panicum maximum (Syn. *Megathyrsus maximus*) cv. Mombasa (Area 1)	Area of pasture over 35 years old, cultivated with Mombasa, with reformed pasture, lime application, without fertilization. This area is managed with dairy cattle, rotational grazing, and animals remaining 30 days in each paddock. Each paddock has an average of 90 days of rest.
Brachiaria brizantha (Syn. *Urochloa brizantha*) cv. Marandú (Area 2)	Area of pasture more than 35 years old, cultivated with *Brachiaria*, with reformed pasture, lime application, without fertilization, and with weeds. The area is managed extensively with dairy cattle.
Brachiaria humidícola (Syn. *Urochloa humidicola*) cv. Humidícola (Area 3)	Area with more than 20 years of pasture, cultivated with *Humidícola*, with reformed pasture, lime application, without fertilization, and with weeds. This area is managed with beef cattle, rotational grazing, and animals remaining 30 days in each paddock. Each paddock has an average of 90 days of rest.
Intercropping (*Urochloa brizantha*; *Urochloa humidicola*) (Area 4)	Area with *Brachiaria brizantha* (Syn. *Urochloa brizantha*) cv. Marandú and *Brachiaria humidícola* (Syn. *Urochloa humidicola*) cv. *Humidícola* intercropped with more than 30 years old, reformed pasture, with lime, mineral fertilization, and cattle manure application and with weeds. This area is managed with beef and dairy cattle, rotational grazing, and animals remaining 15 days in each paddock. Each paddock has an average of 60 days of rest.
Intercropping (*Urochloa brizantha*; *Urochloa humidicola*; *Pennisetum clandestinum*) (Area 5)	An area with *Brachiaria brizantha* (Syn. *Urochloa brizantha*) cv. Marandú, *Brachiaria humidícola* (Syn. *Urochloa humidicola*) cv. *Humidícola*, and *Cenchrus clandestinum* (Syn. *Pennisetum clandestinum*) intercropped, cultivated for more than 20 years, reformed pasture, with lime application, without fertilization, with the presence of pests and weeds. This area is managed with beef cattle, rotational grazing, and animals remaining 30 days in each paddock. Each paddock has an average of 90 days of rest.
Natural pasture (Area 6)	The natural pasture area is characterized by a low plateau in the landscape, with various grassland formations prevailing, with low grassy ligneous formations, with the occurrence of grasses and Cyperaceae of the genera *Andropogon* and *Paspalum* and twisted and spaced trees, such as *Curatela americana* L. and *Eupatorium* sp. It is not used for grazing.
Forest (Area 7)	It is characterized as a dense tropical forest with evergreen vegetation comprising dense, multi stratified trees between 20 and 50 m high.

2.2. Field methodology

Ten sampling points were randomly marked and distributed across each pasture, natural pasture, and forest area. At each of these points, soil samples were taken in the 0.00-0.10 and 0.10-0.20 m depth, this being the depth with the greatest interaction with the root system, as well as the greatest influence on attributes and carbon dynamics, making a total of 20 samples per area, totaling 140 samples. Soil samples were collected in clod form using a volumetric ring to assess physical attributes. In addition, all the collection points were georeferenced so that a location map could be drawn up (**Figure 1**).

2.3. Laboratory analysis

The clods of soil collected were dried in the shade and broken up by hand. They were then passed through a 2.00 mm diameter sieve to obtain air-dried fine earth (ADFE). The particle size analysis was determined using the pipette method (Gee & Bauder, 1986).

To determine the soil penetration resistance (SPR), total porosity (TP), volumetric soil water content (Uv), microporosity (MiP), and macroporosity (MaP), the samples collected in the volumetric rings were saturated by gradually raising a water level in a plastic tray up to two-thirds of the height of the ring. By defining macropores as pores with Ø eq > 300 µm, macroporosity (MaP) was calculated as the ratio between the volume of macropores (volume of water drained between 0 and -1 kPa) and the total volume of the soil (obtained from the volumetric cylinder used to sample the soil). Microporosity (MiP, $cm^3 \cdot cm^{-3}$) was then determined as the ratio between the volume of micropores (Micro) (Ø eq < 50 μm), obtained by the volume of water drained at -6 kPa, and the volume of soil (Teixeira et al., 2017). Total porosity (TP) was calculated from the sum of macroporosity and microporosity measurements, representing all the empty spaces in the soil, whether macropores or micropores.

Soil penetration resistance (SPR) was determined using the same samples collected for assessing porosity, which were determined in the laboratory using an electronic penetrometer with a constant speed of 0.1667 $mm \cdot s^{-1}$ and was equipped with a 200 N load cell, a rod with a 4 mm diameter base cone and a 30° semi angle, receiver and interface coupled to a microcomputer to record the readings using the equipment specific software (Dalchiavon et al., 2011). Volumetric soil water content (Uv) was quantified from the equilibrium on a tension table at the matric potentials of -1 kPa and -6 kPa (Teixeira et al., 2017).

2.4. Statistical analysis

The data obtained from the laboratory analyses was initially subjected to a descriptive statistical analysis (StatSoft, 2004).

Univariate analysis of variance (ANOVA) was used to group the means of the individual attributes using the Scott-Knott test at a 5% significance level. Pearson correlation coefficients were calculated to determine possible relationships between the physical attributes evaluated, such as sand, silt, clay, SPR, Uv, TP, MaP, and MiP.

The suitability of the factor analysis was assessed using the Kaiser-Meyer-Olkin (KMO) measure, which examines the simple and partial correlations of the variables. In addition, the Barlett test of sphericity was used, which seeks to reject the hypothesis of equality between the correlation matrix and the identity matrix.

The factors were extracted using Principal Component Analysis, incorporating the variables with commonalities equal to or greater than five. The number of factors used was determined based on the Kaiser criterion (factors that select factors with eigenvalues greater than 1).

The factors were subjected to an orthogonal rotation (Varimax) and represented in a two-component factor plane to simplify the factor analysis. All multivariate statistical analyses were processed using the STATISTIC software, version 8 (StatSoft, 2004).

3. RESULTS

In both soil depths, the sand content was significantly higher in area 1 (*Panicum maximum* [Syn. *Megathyrsus maximus*] cv. Mombasa) (**Figure 2a**). The silt content was higher in area 7 (forest) in the 0.00-0.10 m but did not differ from area 4 (intercropping between *Brachiaria brizantha* [Syn. *Urochloa brizantha*] cv. Marandú and *Brachiaria humidícola* [Syn. *Urochloa humidicola*] cv. Humidícola and area 5 (intercropping among *Brachiaria brizantha* [Syn. *Urochloa brizantha*] cv. Marandú, *Brachiaria humidícola* [Syn. *Urochloa humidicola*] cv. Humidícola, and *Cenchrus clandestinum* [Syn. *Pennisetum clandestinum*] in the underlying depth (**Figure 2b**). The clay content was significantly higher in area 3 (*Urochloa humidicula*) in both soil depths than in the other areas studied (**Figure 2c**).

In the surface depth (0.00-0.10 m), soil penetration resistance (SPR) was significantly higher in areas 2, 3, and 5, where *Urochloa brizantha*, *Urochloa humidicola*, and *Pennisetum clandestinum* were cultivated, respectively. Meanwhile, areas 1 (*Panicum maximum* (Syn. *Megathyrsus maximus*) cv. Mombasa), 4 (intercropping between *Urochloa brizantha* and *Urochloa humidicola*), natural pasture, and forest showed lower penetration resistance (SPR). In the underlying depth (0,10-0,20 m), areas 2, 3, 4, 5, and the natural pasture showed greater SPR, while areas 1 and the forest showed lower resistance (**Figure 3a**).

Volumetric soil water content (Uv) in the upper depth was similar for areas 1, 2, 3, 4, and 5, with the natural pasture and forest areas standing out as having higher Gm values. However, at a depth of 0.10-0.20 m, areas 2, 4, 5, and 6 showed the highest values, while the lowest value was recorded in the natural pasture area with intermediate values in areas 3 and 2, respectively (**Figure 3b**). Total porosity (TP) in the first depth was higher in area 4, natural pasture, and forest, while areas 1, 2, 3, and 5 showed similar values. In the second depth, all the areas were similar except for the forest area, which had higher porosity (**Figure 3c**).

In the surface depth, soil macroporosity (MaP) stood out in areas 1 and 4, while the other areas had similar porosities. At a depth of 0.10-0.20 m, MaP was more expressive in the forest area, followed by area 1, with less representation in areas 2, 3, 4, 5, and the natural pasture (**Figure 3d**).

In the surface depth, soil microposity (MiP) was significantly higher in area 4, natural pasture, and forest, while lower in areas 1, 2, 3, and 5. In the second depth, all the areas showed similar (MiP), except for area 1, which showed a lower volume of micropores in the soil (**Figure 3e**).

Pearson correlation in the first depth (0.00-0.10 m) revealed that sand content negatively correlated with

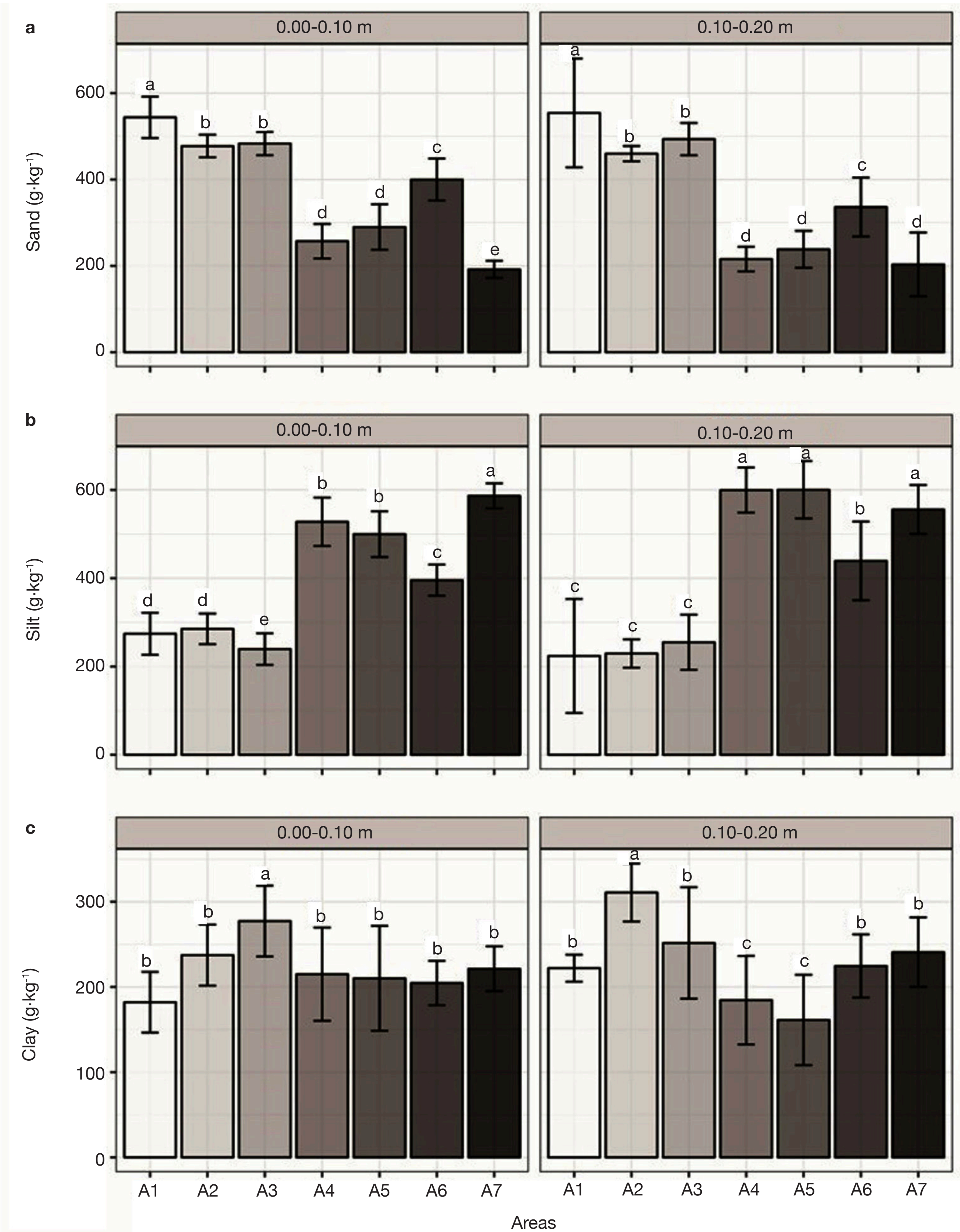

Figure 2. Particle-size (sand, silt, and clay) of soils under conversion from forest to pasture in southern Amazonas, Brazil — *Granulométrie (sable, limon et argile) des sols en conversion de forêt à pâturage dans le sud de l'Amazonas, au Brésil.*

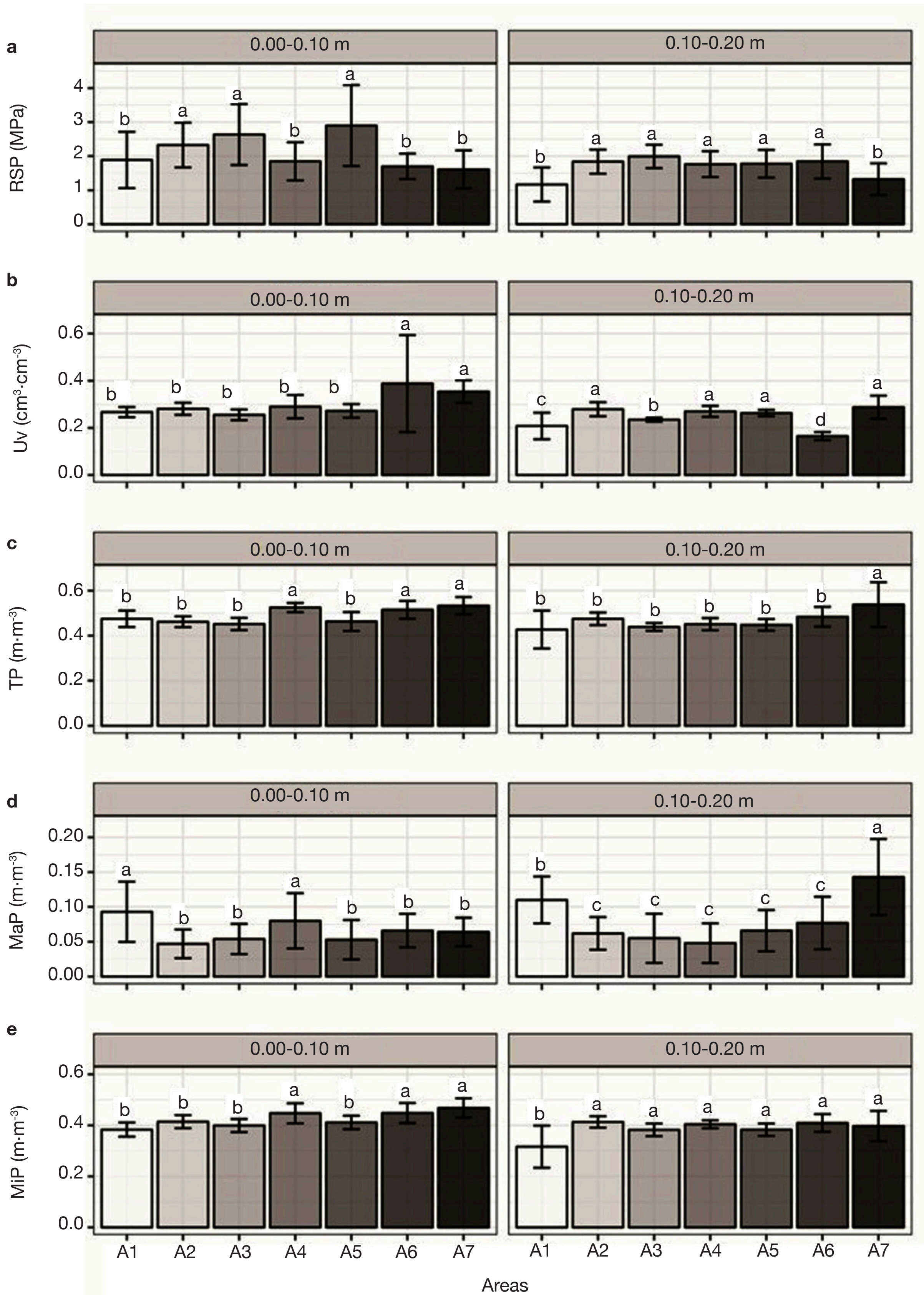

Figure 3. Soil penetration resistance (SPR), volumetric soil water content (Uv), total porosity (TP), macroporosity (MaP), and microporosity (MiP) in areas under conversion from forest to pasture in southern Amazonas, Brazil — *Résistance à la pénétration dans le sol (SPR), teneur volumétrique en eau du sol (Uv), porosité totale (TP), macroporosité (MaP) et microporosité (MiP) dans les zones de conversion des forêts en pâturages dans le sud de l'Amazonas, au Brésil*.

MiP, TP, and silt but no correlation with the other attributes. On the other hand, silt content showed a positive correlation with MiP and TP but a negative correlation with clay content. The resistance of the soil to penetration showed a negative correlation with MaP, TP, and Uv, suggesting a direct relationship where changes in the volumes of MaP, TP, and Uv can significantly affect SPR. The volumetric soil water content correlated positively with TP and MiP. The total porosity showed a positive correlation with MiP, MaP, and silt, while MaP correlated negatively with MiP, indicating an inverse relationship where an increase in the volume of one attribute can result in a reduction in the volume of the other (**Figure 3**).

In the 0,10-0,20 m depth, SPR correlated negatively with MaP and positively with MiP. The volumetric soil water content showed a positive correlation with MiP and TP but a negative correlation with sand content. The total porosity correlated positively with MiP and MaP and negatively with sand content. In this depth, MaP showed no correlation with MiP (**Figure 4**).

In the 0.00-0.10 m depth, the first component (CP1) explained 39.42% of the total variability of the data, the second component (CP2) explained 21.84%, and the third component (CP3) explained 13.68% (**Figure 5**, **Table 2**). It was observed that in CP1, most of the attributes were positively correlated, except for sand, clay, and SPR, which were negatively correlated. In PC2, there was a positive correlation, except for silt, clay, SPR, and MiP. In PC3, most of the attributes were positively correlated, except for MaP and silt (**Table 2**). In the 0.10-0.20 m depth, 34.81% of the total variability was explained by PC1, 24.31% by PC2, and 20.83% by PC3, for the same attributes evaluated (**Figure 5**, **Table 2**). There was a positive correlation between the attributes in PC1, except for sand and clay. In PC2, only silt and SPR showed an inverse correlation. In PC3, the attributes showed a positive correlation, except for TP, MaP, and silt (**Table 2**).

4. DISCUSSION

4.1. Resistance of the soil to penetration (SPR)

It was observed that pasture area 1 (*Panicum maximum* (Syn. *Megathyrsus maximus*) cv. Mombasa) and the forest area showed lower SPR at both depths when compared to the other pasture areas, which showed higher resistances. These results may be related to animal trampling (Lima et al., 2022a), except for area 4 and the natural pasture, which showed lower SPR only on the surface. Related results were found by Pantoja et al. (2019) when evaluating soil penetration resistance in different cropping systems, where pasture areas showed higher resistance values in the topsoil,

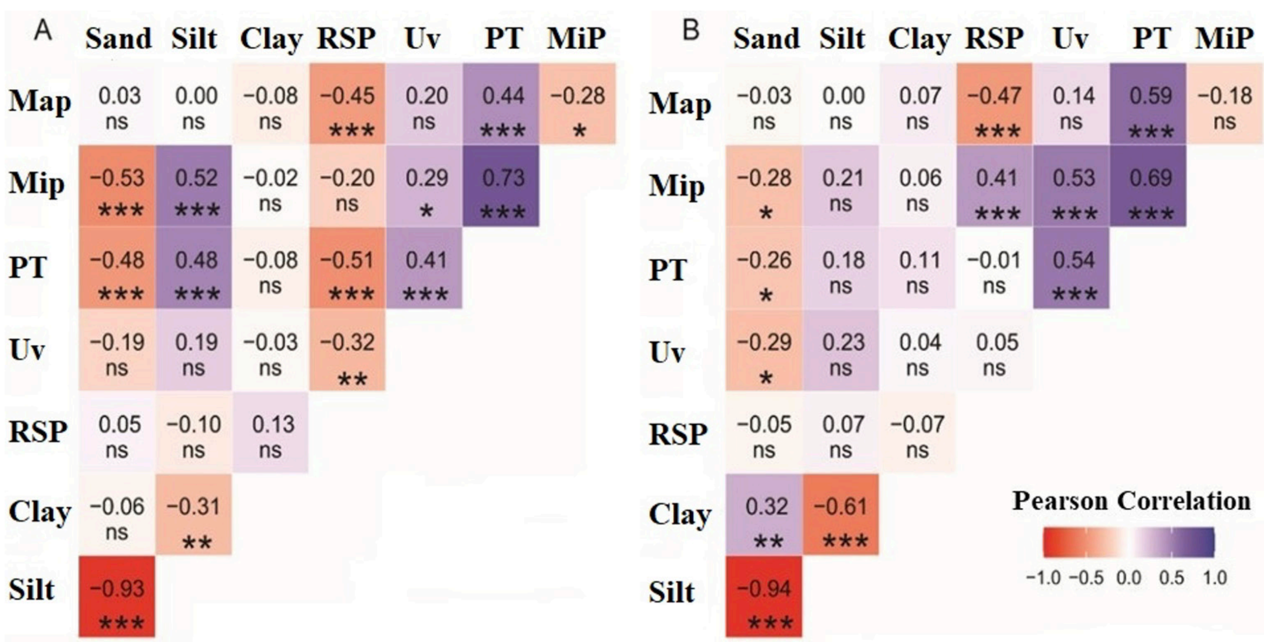

Figure 4. Pearson correlation for particle size, SPR (soil penetration resistance), Uv (volumetric soil water content, TP (total porosity), MaP (macroporosity), and MiP (microporosity) in areas under conversion from forest to pasture in southern Amazonas, Brazil. ns: $p > 0.05$, *: $p \leq 0.05$, **: $p < 0.01$, ***: $p < 0.001$ — *Corrélation de Pearson pour la taille des particules, de la résistance à la pénétration du sol (SPR), de la teneur volumétrique en eau du sol (Uv), de la porosité totale (TP), de la macroporosité (MaP) et de la microporosité (MiP) dans les zones en conversion de forêt à pâturage dans le sud de l'Amazonas, au Brésil. ns:* p > *0,05 ; * :* p ≤ *0,05 ; ** :* p < *0,01 ; *** :* p < *0,001.*

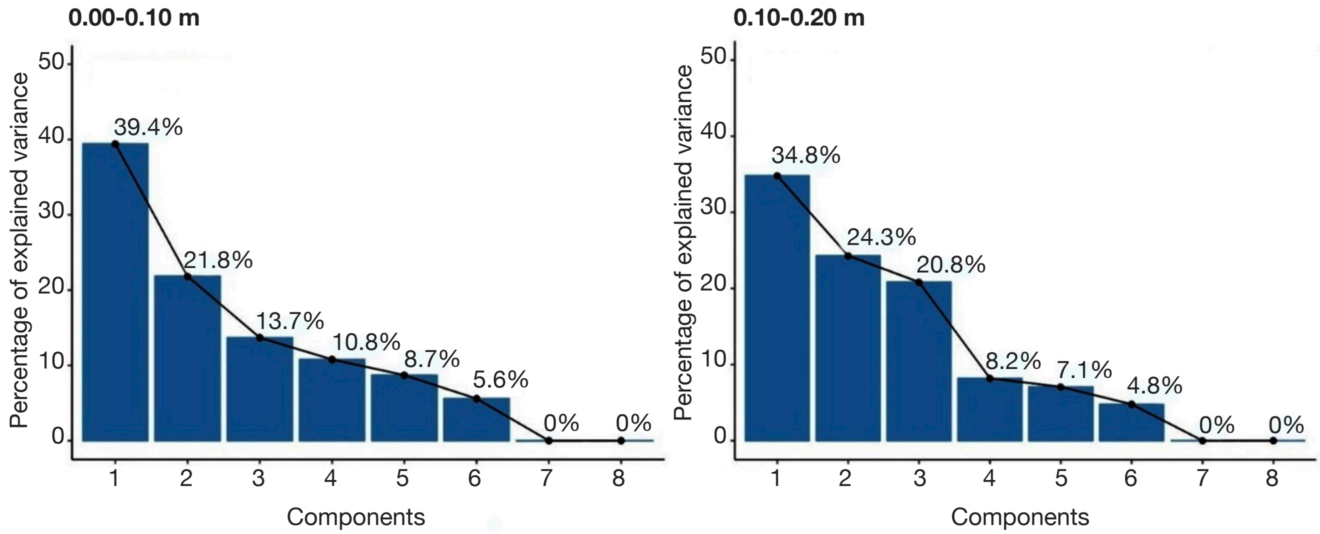

Figure 5. Principal component analysis of particle size, SPR, Gm, TP, MiP, and MaP in areas under conversion from forest to pasture in southern Amazonas, Brazil — *Analyse des composantes principales de la taille des particules, SPR, Gm, TP, MiP et MaP dans les zones en conversion de forêt à pâturage dans le sud de l'Amazonie, au Brésil.*

Table 2. Eigenvalues and eigenvectors of particle size, SPR (soil penetration resistance), Uv (volumetric soil water content, TP (total porosity), MaP (macroporosity), and MiP (microporosity) in areas under conversion from forest to pasture in southern Amazonas, Brazil — *Eigenvalues et eigenvectors de la taille des particules, de la résistance à la pénétration du sol (SPR), de la teneur volumétrique en eau du sol (Uv), de la porosité totale (TP), de la macroporosité (MaP) et de la microporosité (MiP) dans les zones en conversion de forêt à pâturage dans le sud de l'Amazonas, au Brésil.*

Variable	0.00-0.10 m depth			0.10-0.20 m depth		
	Component			Component		
	1	2	3	1	2	3
Sand	-0.780	0.451	0.017	-0.792	0.381	0.235
Silt	0.807	-0.390	-0.340	0.774	-0.546	-0.292
Clay	-0.177	-0.112	0.897	-0.327	0.658	0.276
SPR	-0.468	-0.668	0.230	0.196	-0.264	0.785
Uv	0.498	0.324	0.255	0.654	0.381	0.141
TP	0.872	0.275	0.265	0.689	0.659	-0.044
MaP	0.220	0.807	-0.397	0.159	0.585	-0.698
MiP	0.767	-0.318	0.501	0.697	0.281	0.570
Eigenvalue	3.154	1.747	1.094	2.785	1.945	1.667
Explained var. (%)	39.422	21.838	13.678	34.811	24.308	20.832
Accumulated var. (%)	39.422	61.259	74.937	34.811	59.119	79.951

while forest areas showed lower SPR values, possibly related to soil structuring and organic matter (litter), biological activity and water content. The greater resistance observed at depth in the natural pasture and the pasture area with an intercropping between *Brachiaria brizantha* (Syn. *Urochloa brizantha*) cv. Marandú and *Brachiaria humidícola* (Syn. *Urochloa humidicola*) cv. Humidícola (area 4) may be related to compaction due to the behavior of the crop root system. Studies conducted by Frozzi et al. (2020), when evaluating soil penetration resistance in different use systems (forest conversion to agricultural systems) in the Amazon region, observed that soil compression caused by root growth can contribute to an increase in SPR.

According to Souza et al. (2020), the root systems of different crops influence soil resistance differently, which corroborates the observations of this study.

Root parameters such as diameter, volume, biomass, number, and length play essential roles in modifying soil structure and resistance (Kumi et al., 2016; Foresta et al., 2020) and, therefore, reflect on the root system contribution to soil resistance and stabilization, leading to changes between different land use and occupation systems.

4.2. Volumetric soil water content (Uv)

It was observed that the natural grassland area had higher water content in the surface depth compared to the other pasture areas. The areas with *Brachiaria brizantha* (Syn. *Urochloa brizantha*) cv. Marandú (area 2), intercropping between *Brachiaria brizantha* (Syn. *Urochloa brizantha*) cv. Marandú and *Brachiaria humidícola* (Syn. *Urochloa humidicola*) cv. Humidícola (area 4), and intercropping among *Brachiaria brizantha* (Syn. *Urochloa brizantha*) cv. Marandú, *Brachiaria humidícola* (Syn. *Urochloa humidicola*) cv. Humidícola, and *Cenchrus clandestinum* (Syn. *Pennisetum clandestinum*) (area 5) showed the best results only in the subsurface. Meanwhile, the forest area showed greater water content at both depths.

The possible occurrence of higher water contents in natural pasture areas can be attributed to the high proportions of silt and clay fractions that, associated with the greater presence of micropores, favor greater water retention in these environments. This condition is typical of soils in this type of vegetation and environment, as verified by Mantovanelli et al. (2015).

This condition is widely evident in the natural grassland region of southern Amazonas since one of its characteristics is the predominance of the silt fraction in the topsoil. This is due to the high pedogenetic development of the soils and the characteristics of the region's source materials. Similar studies were conducted by Fonseca et al. (2021) on toposequences in the southern region of Amazonas and Pantoja et al. (2019) studying different land use systems.

4.3. Macroporosity (MaP)

It was observed that pasture area 1 (*Panicum maximum* [Syn. *Megathyrsus maximus*] cv. Mombasa) and area 4, with the intercropping between *Brachiaria brizantha* (Syn. *Urochloa brizantha*) cv. Marandú and *Brachiaria humidícola* (Syn. *Urochloa humidicola*) cv. Humidícola, had higher macroporosity on the surface compared to the other pasture areas, natural pasture, and forest. Area 1, like the forest area, also stood out in-depth, showing significant results.

The results show the importance of forage plants, mainly in improving structure and increasing macroporosity. However, it is important that the producer manages the soil consciously, not exceeding the maximum support capacity of the pasture.

Forage plants have a direct influence on soil aggregation, structuring, and permeability due to the aggressive growth of the root system, allowing deeper exploration of the soil profile, providing greater absorption of water and nutrients, aiming at better production of dry mass (Santos et al., 2020; Bello et al., 2021).

It is plausible to associate the higher porosities with the presence and influence of organic matter on soil structuring, according to Silva et al. (2016). In addition, this porosity may be related to the root renewal capacity of forage plants, playing a significant role in soil decompression. Studies by Hassane et al. (2023), evaluating the physical attributes of soils in the Amazon region cultivated with tropical forage under grazing, corroborate this perspective.

Pasture and natural grassland areas that showed low volumes of macropores in the upper depth and the subsurface may be related to soil compaction. Studies conducted by Gomes et al. (2019), when evaluating the physical attributes of the soil in different cover crops, showed that increased soil compaction could result in a reduction in macroporosity, soil aeration, plant height, and root dry matter. In addition, its low quantity can limit the water flow in the soil profile and gas exchange, thus harming biological activity in the soil (Souza et al., 2019).

4.4. Microporosity (MiP)

It was observed that the area with a consortium of *Brachiaria brizantha* (Syn. *Urochloa brizantha*) cv. Marandú and *Brachiaria humidícola* (Syn. *Urochloa humidicola*) cv. Humidícola (area 4), natural grassland, and forest showed the highest microporosity values, both in the surface depth and at depth. On the other hand, pasture area 1 (*Panicum maximum* [Syn. *Megathyrsus maximus*] cv. Mombasa) showed a lower representation of micropores at both depths, while the other pasture areas showed higher values in the subsurface depth.

Therefore, it is worth noting that microporosity is responsible for retaining and storing water in the soil (Gomes et al., 2019), and according to studies carried out by Lima et al. (2022a) evaluating the physical properties of the soil, microporosity suffers little influence from vegetation cover and traffic on the soil, showing intrinsic characteristics with texture and organic matter content, which may corroborate the results found in area 4, natural pasture, and forest.

4.5. Total porosity (TP)

It was observed that the pasture area with intercropping between *Brachiaria brizantha* (Syn. *Urochloa brizantha*) cv. Marandú and *Brachiaria humidícola* (Syn. *Urochloa humidicola*) cv. Humidícola (area 4) and the natural pasture had the highest total porosity at the surface compared to the other pasture areas. Meanwhile, the forest area showed higher results at both depths.

This reflects that TP is related to the level of soil degradation. Reduced porosity can occur due to soil compaction, increased density that impacts biological activity and infiltration capacity, exposing the soil to erosion processes (Souza et al., 2019). Total porosity is an indicator of soil quality, directly reflecting pressure changes caused by animal trampling due to excessive use of animals in the same area (Hassane et al., 2023). These practices are not common in forest environments, which ensures the presence of pores that contribute to a better structural and water quality of the soil. On the other hand, the decrease in total porosity at surface or subsurface depths in pasture areas may be associated with the excessive use of large animals, even in areas where animal rotation is carried out.

As highlighted by Neto et al. (2018) in their evaluation of organic matter and physical water attributes of a latosol under different management systems, it was observed that total porosity values of less than 0.5 $m \cdot m^{-3}$ can be associated with soil management, which normally reduces porosity through soil compaction and densification. In addition, the predominance of the sand fraction may influence the smaller presence of pores inside the aggregates, resulting in a decrease in total porosity.

In the study conducted by Mantovanelli et al. (2015), similar patterns were identified in the physical indicators of soils in native grassland areas, associating these conditions of high levels of densification with high silt contents, which stood out or corresponded to the sum of the sand and clay contents. This scenario favors the clogging of pores and exposes the soil to destructive processes, such as seasonal fires during the dry season, favored by the vegetation cover itself, consequently resulting in reduced porosity values in the southern Amazonas.

5. CONCLUSIONS

The conversion from forest to pasture changed the physical properties evaluated. So that, in the 0.00-0.10 m depth, the forest and natural pasture areas stand out for their higher volumetric soil water content, microporosity, and total porosity. In contrast, the pasture areas are characterized by higher soil penetration resistance. As well as, in the 0.10-0.20 m depth, the forest area stands out for its volumetric soil water content, macroporosity, and total porosity, while the natural pasture and pasture areas show greater soil penetration resistance and microporosity. Seeking a greater understanding of the physical-hydric dynamics of Amazonian soils, more studies are needed to evaluate their relationships with physical, chemical and biological attributes.

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