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Research Article

Physical Quality and Porosity Aspects of Amazon Anthropogenic Soils under Different Management Systems

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Archaeological Dark Earth (ADE) soils are rich in organic matter and highly fertile, but when used for farming or grazing activities, they generally lose chemical and physical quality, becoming more susceptible to erosion. In this context, this study aimed to evaluate the changes in physical properties of the soil in different management systems adopted in ADE areas of the Amazon. The study area is located in the municipality of Novo Aripuanã, in the mesoregion of Madeira, south of the state of Amazonas. Three ADE areas were selected: 1—native forest (Amazon forest fragment); 2—area covered with Brachiaria (*Urochloa brizantha* cv. *Marandu*), without the addition of fertilizers or soil improvers; and 3—area covered with pigeon pea (*Cajanus cajan*) and other commercial crops (corn, beans, and watermelon). The following soil characteristics were evaluated: soil resistance to penetration, soil bulk density, macroporosity and microporosity, and total soil porosity in the 0–0.20 m and 0.20–0.40 m layers. The results showed that the pasture area presented a smaller amount of total pores and complex pores, which are important for water flow in the soil. The areas analyzed in this study presented no critical obstacle to plant root development with the low value of resistance to penetration (<2.00 MPa) in all areas.

1. Introduction

The southern region of the state of Amazonas covers around 474,000 km^2, corresponding to 30% of the total area of the state. These areas have a high diversity of geological materials, with different types of soils, which are usually highly weathered, deep, acid, of poor fertility, presenting high mineralization of organic matter [1]. However, the same region also has soils of dark anthropic A horizon (Au), containing ceramic and/or lithic fragments incorporated into the matrix of the superficial soil horizons, which are known as *Terra Preta de Índio* or Archaeological Dark Earth (ADE) [2].

ADE soils have on average up to six times more stable organic matter than adjacent soils and are considered a large reservoir of organic carbon [3]. Santos et al. [4] point out that these soils offer high natural fertility, probably due to long-term anthropic occupation and incorporation of pyrogenic carbon of high cation exchange capacity (CEC). According to [5], ADE soils occur in discontinuous areas across the Amazon and its main use by local populations is subsistence agriculture.

However, the anthropic occupation of existing ADE areas in the Amazon has negatively impacted their biodiversity, especially in terms of soil conservation and proper vegetation recovery [5, 6]. According to [7], soil quality is reduced as ecosystems are replaced by anthropic activities. Several studies have been conducted using physical properties as indicators of changes in soil to analyze the impact from different management systems; these indicators include soil resistance to root penetration, bulk density, macro- and microporosity, total porosity, water retention ability, and soil aggregate stability [5, 8–11].

Studies about the physical quality of soils using micromorphology techniques to analyze soil structure and changes in micrometer scale have become increasingly popular. According to [12], this technique refers to impregnation of a dry soil with a fluorescent resin, which, after being cut into slices, can be analyzed by optical microscopy; the material, in contact with the ultraviolet light, has its empty areas (pores) illuminated, allowing their evaluation. According to [13] analyzing undisturbed samples impregnated with resin may provide important information for the soil management diagnosis.

Soil evaluation through micromorphology is used in several areas, for example, to evaluate traffic control in areas of sugarcane [6], orange [14], and bean crops [15] where differences can be observed in pore size, shape, and quantity when comparing soil treatments. In this context, this study aimed to evaluate the changes in physical properties of the soil in different management systems adopted in ADE areas of the Amazon, using micromorphology techniques. The hypothesis that ADE soil conversion into pasture and plantation of pigeon pea reduces the physical quality of the soil in relation to the native forest was tested in this study.

2. Materials and Methods

2.1. Study Area Description. This study was conducted in the municipality of Novo Aripuanã, located in the mesoregion of Madeira, south of the state of Amazonas, between 07°51′30″ south latitude and 61°18′01″ west longitude and average altitude of 40 m [16] (Figure 1).

The soil of the experimental area presents sand texture (Table 1) and has been classified as Latossolo Amarelo eutrófico argissólico, according to the Brazilian Soil Classification System (SiBCS) [17] or as Typic Haplohumult, according to soil taxonomy [18].

The region has plateaus in its higher lands and plains in the lower parts, whose main features are the presence of pediplain surface, locally interrupted by flat-topped hills [19]. The region has tropical rainforest climate, according to the Köppen classification, with a short dry period and rainy season between October and June. The average annual rainfall, temperature, and relative humidity range between 2,250 and 2,750 mm, 25 and 27°C, and 85 and 90%, respectively [20].

Three ADE areas were selected: 1—native forest (Amazon forest fragment) that has been preserved for over 25 years with large secondary trees, between 15 and 20 meters high; 2—area covered with Brachiaria (*Urochloa brizantha* cv. *Marandu*), implemented seven years before for extensive grazing, with 2.1 heads/ha, without pasture division and no addition of fertilizers or soil amendments; and 3—area covered with pigeon pea (*Cajanus cajan*) and other native climbing plants, and in the past 25 years, the last two areas have had corn, bean, and watermelon plantations.

2.2. Soil Sampling and Laboratory Analysis. Undisturbed samples were collected from mini-trenches at 0.00–0.20 m and 0.20–0.40 m layers of the three soil systems (native forest, pigeon pea, and pasture). For micromorphological characterization, soil monoliths were collected using rectangular white cardboard boxes measuring 0.07 m × 0.12 m × 0.06 m. In addition, during monolith collection, samples were collected with steel cylinders of 0.05 m height and 0.05 m diameter to evaluate the soil resistance to penetration, soil bulk density, and macro- and microporosity. So, we had four soil results in just one sample soil collected, that is, macroporosity, penetration resistance, microporosity, and bulk density.

Each soil system was sampled in triplicate, randomly distributed in the areas, totaling 18 samples of soil monoliths and 18 of the soil in the steel cylinders.

Soil bulk density (kg dm^{-3}), macroporosity (m^3 m^{-3}), and microporosity (m^3 m^{-3}) were determined according to the methodologies developed by [21], as follow: first, the samples were saturated by capillary action until total drenching and, then, were placed on the tension table at 60 cm of water column, to determine the microporosity after leaving for 24 h on the table [20]. This 60 cm creates a tension of 6 kPa (the average matrix potential for tropical soils ranges from 6–10 kPa). After, the sample were standardized in soil moisture to penetrometer analysis on the table. Once the reading was done, the samples were oven-dried at 100°C for 24 h and the dry weight was determined by weighing using an analytical balance.

Soil resistance to penetration was determined in samples with moisture equilibrated at tension of 60 cm of water column according to [22] using an electronic penetrometer, Marconi manufacturer, Model MA-933® with constant displacement speed of 1.0 cm min^{-1}, equipped with 200 N load cell, a rod of 4.0 mm cone diameter and 30° semi-angle, and a receiver and interface connected to a computer to record the readings using the equipment software.

For the micromorphological analysis, air-dried monoliths were impregnated by capillary in a vacuum chamber with a mixture of polyester resin, styrene monomer, and Tinopal OB fluorescent pigment, using Butanox as catalyst for resin polymerization [23]. To each 1,000 mL of resin, 1,000 mL of styrene monomer (1 : 1 ratio), 4.0 drops of Butanox, and 2.0 g of fluorescent pigment were added. For greater impregnation efficiency and easy resin penetration, the samples were placed in a desiccator connected to a pneumatic pump, creating a closed vacuum system kept in a fume hood for at least 24 hours. After this step, the

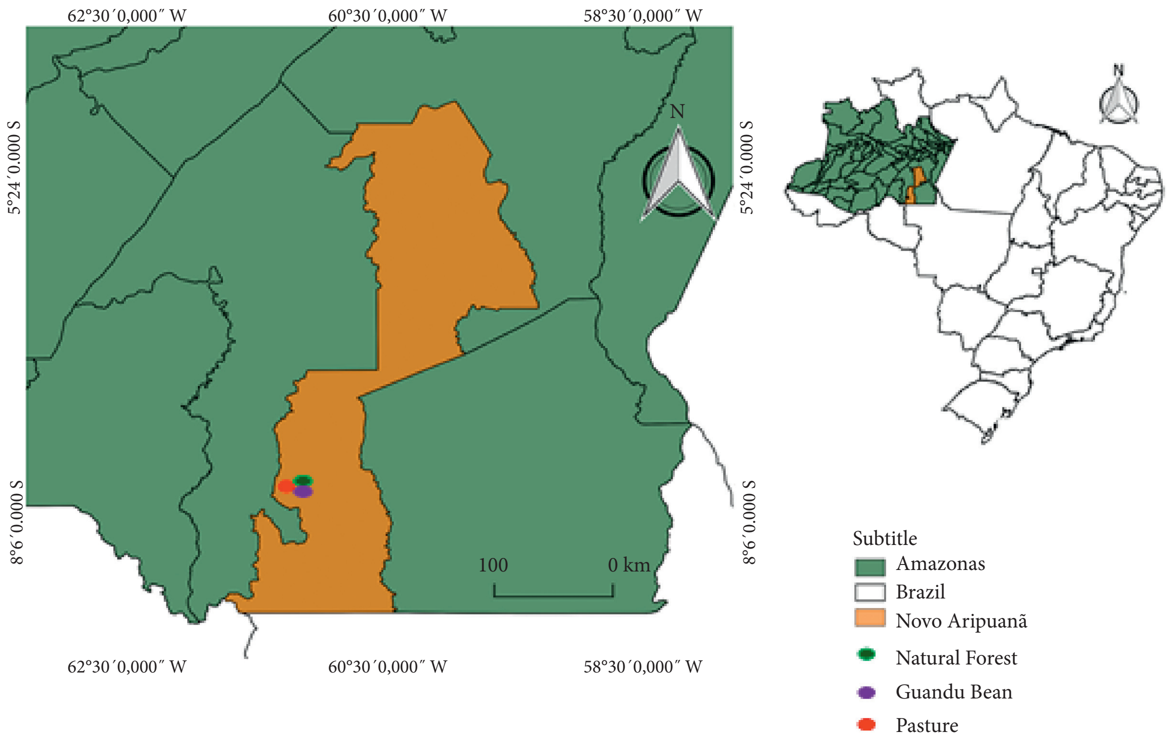

Figure 1: Location of study areas in the municipality of Novo Aripuanã, state of Amazonas, Brazil.

Table 1: Soil particle distribution and organic matter of the Archaeological Dark Earth at 0.0–0.20 m depth layer with different soil managements at Novo Aripuanã, Amazonas.

Soil management	Sand	Silt	Clay	SOM
		$g{\cdot}kg^{-1}$		
Native forest	707.06	197.77	95.17	36.66
Pigeon pea	755.39	159.25	85.36	39.66
Pasture	749.6	166.93	83.46	36.56

impregnated pieces remained in a fume hood for 30 days until the resin was completely hardened. After hardening, the pieces were cut using a diamond saw to eliminate excess resin from the sample to a thickness of about 5.0 mm. The pieces were polished on one side with carborundum powder in a rotating disc until a flat surface was obtained to produce images.

Scanned images were produced using a CCD camera, pixel resolution of 102×768, and area per pixel of $156.25\,\mu m^2$. The images were processed on a SUN Spark IPC system using Noesis Visilog® image analysis software 5.4.

Total porosity (TP) was calculated as the sum of the areas of all pores divided by the total area of the image as a percentage. These pores were divided into three groups according to their shape: round, elongated, and complex. Two indices were used to determine the pore shape, according to [23]

$$I_1 = \frac{P^2}{4\pi A}, \tag{1}$$

where I_1 is Index 1, P is the pore perimeter, and A is the pore area.

$$I_2 = \frac{(1/m)\sum_i (N_i)_i}{(1/n)\sum_j \left(D_f\right)_j}, \tag{2}$$

Here, I_2 is Index 2, N_i is the number of intercepts of an object in "i" direction ($I = 0$, 45, 90, and 135), D_f is the Feret diameter of an object in "j" direction ($j = 0$ and 90), m is the number of "i" directions, and n is the number of "j" directions. I_2 is used as a complement to I_1 for higher precision in the categorization as round, elongated, and complex pores.

With the images showing the pore shapes, the pores could be identified, in which channels, isolated cavities, and tubular pores belong to the category of pores of shape index $I_1 \leq 5$ and define the morphological class of round pores (Rd). The pores resulting from the assemblage of aggregates or elementary particles or interconnected pores of different types, creating in both cases a large pore network of very complex shapes, belonged to the pore category of shape index $I_1 > 25$, defining them as complex pores (Comp) [24].

The range of shape indices I_1, from 5 to 25, has elongated and complex pores, usually smaller than the preceding ones. In this case, I_2 was defined to set the limits of I_1, which allowed a better definition of elongated pores (Elon) $I_2 \leq 2.2$ and complex pores (Comp) $I_2 > 2.2$.

The three pore shapes—round (Rd), elongated (Elon), and complex (Comp)—were compared to pore sizes on the scale used in this study. Then, nine pore types were defined according to their shape and size: small, midsize, and large round pores (Rds, Rdm, and Rdl); small, midsize, and large elongated pores (Elons, Elonm, and Elonl); and small, midsize, and large complex pores (Comps, Compm, and Compl). Size classes were defined as follows: small pores (S) (156–15,600 μm^2), medium (M) (15,601–156,000 μm^2), and large (L) (>156,000 μm^2) [24].

2.3. Statistical Analysis. Significant differences between treatments were evaluated by analysis of variance (ANOVA) using the F test, in which, when presenting significance, means were separated using Tukey's test considering 5% probability. Both tests were performed on R software [25].

Table 2: Mean values of soil resistance to penetration (RP), soil bulk density (Bd), macroporosity (Ma), microporosity (Mi), total porosity (TP), and macropore density (Ma/TP) in Archaeological Dark Earth (ADE) areas receiving three different management systems.

Soil Management	RP MPa	Bd $kg{\cdot}dm^{-3}$	Ma	Mi $m^3{\cdot}m^{-3}$	TP	Ma/TP —
			0.00–0.20 m			
Native forest	1.10 b	1.26 b	0.27 a	0.29 a	0.56 a	0.48 a
Pigeon pea	1.32 ab	1.27 b	0.26 a	0.29 a	0.54 b	0.48 a
Pasture	1.46 a	1.36 a	0.19 a	0.32 a	0.51 c	0.37 b
			0.20–0.40 m			
Native forest	1.15 a	1.34 a	0.24 a	0.29 a	0.54 a	0.44 a
Pigeon pea	1.23 a	1.35 a	0.21 a	0.31 a	0.52 b	0.40 a
Pasture	1.36 a	1.41 a	0.17 a	0.32 a	0.49 c	0.35 b

3. Results

When analyzing the mean values of the physical attributes evaluated in this study, soil resistance to root penetration and soil bulk density were significantly higher in the pasture area when compared to the areas of pigeon pea and native forest in the 0.00–0.20 m, while total porosity was higher in the native forest in both depth layer ranges. In the 0.20–0.40 m soil layers, no difference ($p > 0.05$) was observed between the management systems in terms of soil resistance to penetration, soil bulk density, macroporosity, and microporosity (Table 2).

Regarding soil porosity, the values from native forest were significantly higher ($p < 0.05$) when compared to pigeon pea and pasture in both 0.00–0.20 m and 0.20–0.40 m. layers. Macropore density (relation Ma/TP) ranged from 0.35 to 0.48 in different soil management systems, all above 0.33, which is considered a limiting factor for root growth.

The areas of pigeon pea and native forest showed the predominance of large complex pores (higher than 500 μm) in depth of 0.00–0.20 m and 0.20–0.40 m layers (Figure 2). However, this behavior was not seen in the pasture area.

When analyzing the distribution of pore size in the area of pigeon pea, reduced pore area of the samples was observed, and an increase in large complex pores was observed (Figure 2). Pores ranging from 50 to 500 μm (micropores according to classification of Embrapa) [21] accounted for 39 and 53% of the area of round and elongated pores, showing an increase in depth layer. The contribution to the total pore area per image (TPI) decreased from 28% (0.00–0.20 m layer) to 25% (0.20–0.40 m layer). Regarding these contributions, round pores increased in depth layer when compared to complex pores.

Pore variation from 20 to 50 μm for all depth layers and soil management systems presented a small percentage, between 1.23% and 2.82%, with a small increase in round pores for pasture when compared to pigeon pea and native forest.

Regarding the native forest area, the contribution to TPI due to pores of 50 to 500 μm was 40% for the soil layer of 0.00–0.20 m and 45% for 0.20–0.40 m layers (Figure 2). However, complex pores presented smaller values when compared to the pores of 50–500 μm, which decreased from 59% to 54% between the two soil layers. TPI for the layers was 28% and 27%, respectively, with a similar standard deviation, from 4.2% to 4.5%, mainly due to reduction in complex pores larger than 500 μm and increase in round and elongated pores of 50–500 μm.

Regarding the pasture area, significant differences ($p < 0.05$) were observed when compared to the areas of pigeon pea and forest, as TPI had an increase in depth layer from 19% to 20%, with standard deviation from 4.5% to 2.7%, respectively (Figure 2). However, the variation of complex pores larger than 500 μm and pores of 50–500 μm in the pasture area was similar to that of pigeon pea and forest. This variation occurred due to a reduction in complex pores (<500 μm) from 31% to 28%, associated with the increase in pores of 50–500 μm from 66% to 70%; however, a variation between depth layer was observed.

The contribution of round and elongated pores of 50–500 μm and complex pores (<500 μm) presented the highest TPI in the evaluated areas and soil layers, which were greater than 95%, but the pasture area presented the lowest indices of complex pores (<500 μm) at both soil layers when compared to other soil managements (Figure 2). This lower percentage of complex pores (<500 μm) is associated with higher soil bulk density (1.36 and 1.41 $kg{\cdot}dm^{-3}$) and microporosity (0.32 $m^3{\cdot}m^{-3}$) and lower macroporosity (0.19 and 0.17 $m^3{\cdot}m^{-3}$) (Table 1).

The total number of pores showed a similar trend for all areas and depth layers studied and had an influence of complex pores <500 μm, which significantly contributed to TPI (Figure 3).

Regarding the area of pigeon pea, 15 complex pores were smaller than 500 μm, which represents about 57% of the TPI in the soil layer range of 0.00–0.20 m (Figure 3). The amount of large complex pores increased in the layer range of 0.20 to 0.40 m, from 15 to 17; however, its contribution to the TPI was 43%.

In the area of native forest, pore number was similar in both soil layer ranges, except for round pores of 20–50 μm to 50–500 μm, which ranged.

In the pasture area, pores larger than 500 μm presented constant values in soil layer ranges; however, in 20–50 μm and 50–500 μm diameter classes, a decrease was observed

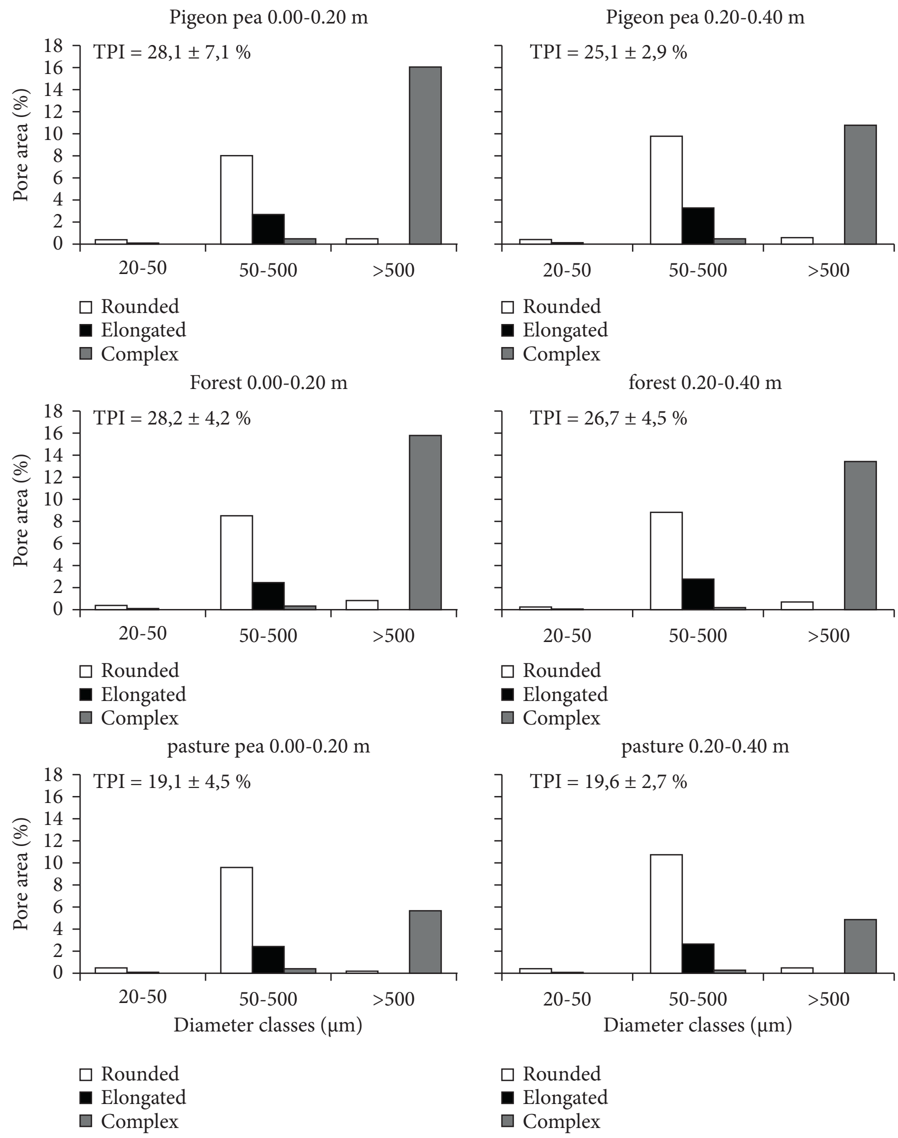

Figure 2: Pore areas according to shape and size from ADE areas with pigeon pea, pasture, and native forest, in soil layer of 0.00–0.20 m and 0.20–0.40 m. TPI = total pore area per image.

in the amount of pores, except for round pores of 50–500 μm, which increased from 905 to 932; however, their contribution to this increase was not significant for the TPI.

This large amount of round pores present in different soil uses can be divided into two types based on their origin: (i) spherical pores resulting from air trapped during the soil drainage process and (ii) development of channels and chambers due to biological activity (roots and earthworms). Microscope images showed changes in pores due to a greater difference between pasture and the other areas, as the dark soil matrix presents larger areas when compared to the other areas, especially in the lateral regions of the image (Figure 4).

When analyzing the depth layer ranges, an increase was observed in the areas containing the solid (black color), that is, total porosity (white color) reduced with soil depth, mainly in the pasture.

4. Discussion

The pasture system showed the highest Bd (kg·dm^{-3}) and this value is according to Brito et al. (2018), who studied ADE in the systems of under cocoa, coffee cultivation, and pasture and concluded that the pasture showed higher values of bulk density (1.30 Mg·m^{-3} in 0.00–0.05 m layer). However, this Bd value did not exceed the critical limit for sandy soils of 1.60 and 1.65 Mg·m^{-3} reported by Araujo et al. [26] and 1.60 Mg·m^{-3} [27], respectively.

This increase in Bd is usually indicative of a soil with greater resistance to root growth, reduced aeration that has difficult gas exchange, and low hydraulic capacity [28]. These results can be justified by animal trampling and the high number of cattle and intensive grazing, which, when associated with the lack of nutrient replacement via fertilization and use of improvers, does not provide sufficient vegetation cover to minimize the effect of intensive cattle trampling and

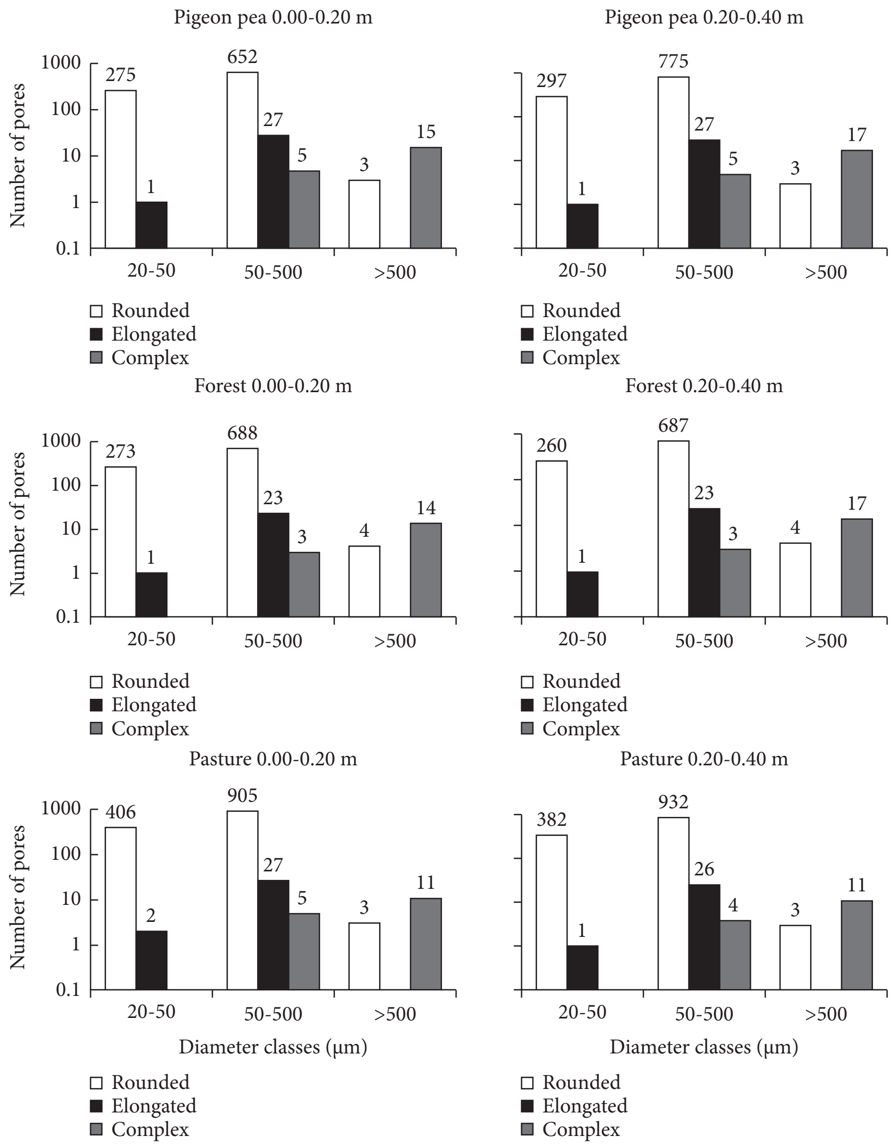

Figure 3: Number of pores according to shape and size from ADE areas with pigeon pea, pasture, and native forest, in soil layer ranges of 0.00–0.20 m and 0.20–0.40 m.

increase soil evaporation. In a study about the physical characteristics of soil in pastures with black oats and ryegrass, [29] observed that the high number of cattle in a short period caused topsoil compaction. Reference [30] also reported that the degree of compaction caused by cattle trampling is influenced by soil texture and moisture, grazing system, and pasture plant height. According to Ralich et al. (2008), the highest values of soil resistance to penetration occur in more superficial layers (0.00–0.10 m) in pasture areas, due to animal trampling.

Although the pasture soil had high values of soil resistance to penetration and soil bulk density, it cannot be considered compacted soil as the values are below the limit of 2.0 MPa, which is considered critical for root development in several studies [31, 32]. For soil bulk density, critical values for the development of these crops are above 1.60 kg dm^{-3}, but his level was not found in this study [26, 33].

In addition, even with reduced macroporosity in the pasture area, macropore density indicated no obstacle to root development. According to [34], around one third (1/3) of the total porosity of the soil must correspond to macropores and lower values indicate limited space for satisfactory root development and possible compaction. Reference [35] reports that the critical limit of macroporosity considered an obstacle for root growth is 0.10 $m^3 \cdot m^{-3}$ for annual crops, and optimal soil is 1/3 macropores (34%) and 2/3 micropores (66%). Reference [36] highlights that the limit value of 0.10 $m^3 \cdot m^{-3}$ macroporosity represents the reference value that limits root growth, water percolation, and gas exchange through soil.

During the soil compaction process, macropores that promote soil aeration decrease and are replaced with micropores; this process shows the negative effect of machine traffic during the soil management [37]. According to [38],

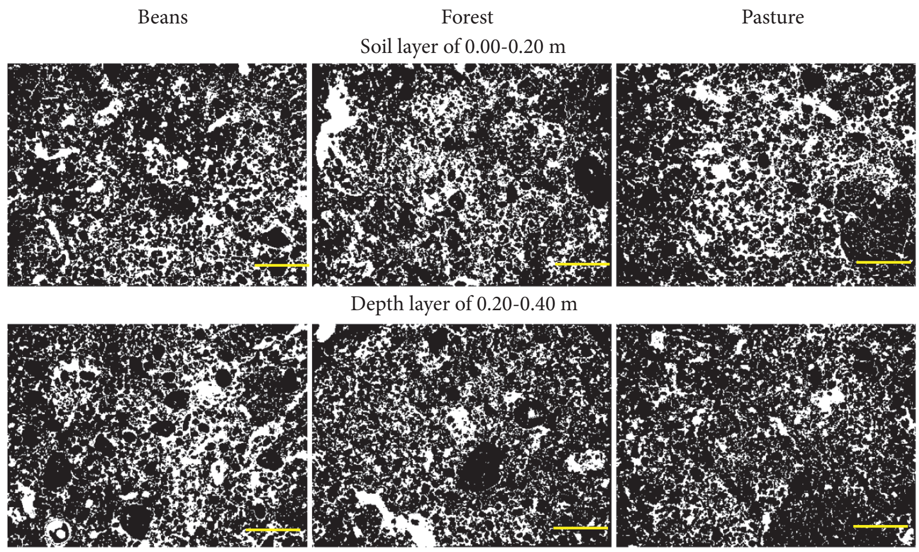

Figure 4: Binary images representing variations in soil structure in areas with pigeon pea, pasture, and native forest in different depth layer ranges (1000 μm scale in yellow). Colors: black (solid) and white (pore).

the soil resistance to penetration and soil bulk density are important and widely used attributes in soil quality evaluation as these parameters are sensitive to changes due to soil management. According to [9], soils with greater resistance to penetration and soil bulk density present lower total porosity, and this can reduce permeability and water infiltration, affecting the physical quality of the soil.

Higher values of total porosity, regardless of the depth layer evaluated in this study, were obtained in the native forest area, where the absence of soil inversion and constant renewal of the root system associated with the diversity of fauna and flora are factors that influenced this result. Several studies have reported lower values of soil bulk density and higher total porosity in native forest area when compared to other soil management systems (conventional tillage, pasture, and no tillage), which are justified by the higher accumulation of plant and organic carbon residues in the superficial layers, remaining root system of existing plants, and absence of anthropic changes [4, 8, 39].

In addition, soil bulk density values, regardless of the soil management systems in ADE areas, were below the values found for mineral soils used for pasture and pigeon pea of 1.32 to 1.56 $kg \cdot dm^{-3}$. According to [40], lower soil bulk densities and higher total porosity in ADE areas result from the intense biological activity of the soil that builds channels, cavities, and chambers. In the same soil cultivated with corn, [6] found soil bulk density of 1.30 $kg \cdot dm^{-3}$, which is similar to the findings of this study for the area of pigeon pea, demonstrating that soil management has changed the physical quality of these soils.

When analyzing the microscope images obtained in this study, total porosity remained higher in the native forest; that is, data from images confirm the results found with the direct method. The lowest value of total porosity was found for pasture due to intrapore variations, which are visible only when evaluated on a microscope. This result can be a result of animal trampling, where the higher weight of animals versus humans tends to destroy pore structure, as demonstrated by [41].

Despite this, in all areas evaluated in this study, total porosity was above 49%, which demonstrates that the areas have no compaction issues, as indicated by the low values of soil resistance to penetration and soil bulk density. According to [42], when analyzing soil through images, a soil is considered compacted when its total porosity is less than 10%, moderate porosity is between 10% and 25%, and high porosity is between 25% and 40%. According to [43], when total porosity decreases, macroporosity also decreases and microporosity increases, reducing water infiltration through soil.

Also, an increase was observed in complex pores (larger than 500 μm) at pigeon pea and forest areas; however, round pores prevailed with depth layer in all areas. Reference [44] highlights that complex pore reduces physical limitations to root growth, which can increase crop productivity. According to [41], complex pores are common empty spaces of the soil, characterized by irregular walls or pores developed between microaggregates or sand grains in soil.

When analyzing soil structure under irrigated beans in different soil management systems, [23] observed that in a no-tillage area, a greater water movement along the profile was due to the predominance of complex pores (larger than 0.156 mm^3) in the soil layer range of 0.20–0.40 m, while in conventional tillage, round pores were predominant. The predominance of rounded pores reflects in the reduction in the continuity of porous channels, reducing the permeability of the soil [42], and mechanized operations on agricultural soil promote changes in soil porosity.

These changes in total porosity indicate loss of water circulation in the profile as pores become smaller and less interconnected. Studies reported that a decrease in elongated pores with size of 0.5–50 μm affects plant growth and root penetration because of storage pores of water, while the elongated pores decreased with 50–500 μm affecting soil the permeability and distribution of water and gases because of the pore of transmission [45, 46]. Another study, when studying soil micromorphology and its relations with physical and water attributes, greater water movement was found along the profile through complex pores, mainly in the pores > 50 μm [47].

The pasture area presented greater soil compaction in the subsurface and, consequently, fewer complex pores, which can reduce pore connectivity and less water circulation along the soil profile when compared to the areas of native forest and pigeon pea. References [48, 49] reported fewer interconnected pores in compacted regions due to machine traffic when compared to less compacted regions. In a recent study, [50] demonstrated that compaction reduces the large pores and the amount of interconnected pores.

Another characteristic of ADE areas is the absence of heavy implements and intensive tillage, which cause physical damage to the soil. Then, pores found in these areas contain high amounts of round pores, leading to more water retention in ADE areas.

5. Conclusions

The areas analyzed in this study presented no critical obstacle to plant root development. The pasture area presented a smaller amount of total pores and complex pores, which are important for water flow in the soil.

Data Availability

The number data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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