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Soil physical attributes in a native forest area and plantations of *Bertholletia excelsa* Bonpl. in the Central Amazon[1]

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ABSTRACT - Soil physical quality is an important indicator of environmental sustainability; therefore, its evaluation is essential for the adoption of appropriate management practices. The objective of this study was to evaluate soil physical attributes in a native forest environment (NF) and in areas cultivated with Brazil nut (*Bertholletia excelsa*), aged 3 years (CA3, previously under pasture) and 25 years (CA25), located in the municipality of Itacoatiara, Amazonas, Brazil. Sampling grids of 70 m × 70 m were established with a 10 m spacing, totaling 64 sampling points. Soil samples were subsequently collected from the 0 – 20, 20 – 40, and 40 – 60 cm layers to determine soil texture, macroporosity, microporosity, and total porosity; soil bulk density; soil penetration resistance; and aggregate stability. The data were analyzed using descriptive and multivariate statistics. The pasture history in CA3 contributed to increased penetration resistance (PR = 2.35 MPa) and bulk density (Bd = 1.31 g cm^{-3}) in the upper 0–20 cm layer. Higher values of macroporosity (Ma = 0.14 $m^3 m^{-3}$) and total porosity (TP = 0.60 $m^3 m^{-3}$) were observed in the surface layer of the native forest (NF). The CA25 area was characterized by lower bulk density in all layers and greater soil aggregation, with higher values of geometric mean diameter (GMD = 2.65 mm), mean weight diameter (MWD = 3.11 mm), aggregate stability index (ASI = 95.88%), and aggregates > 2.00 mm (90.31%). Based on principal component analysis, soil aggregation and porosity were the main attributes distinguishing the CA3 Brazil nut area from other areas in the topsoil layer.

Keywords: Brazil nut tree. Soil quality. Amazonian soils. Forest soils.

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INTRODUCTION

Soil is considered a non-renewable natural resource that plays a fundamental role in providing ecosystem services essential for maintaining the quality and well-being of terrestrial fauna and flora and, therefore, serves as the foundation of all human production systems (Karaca *et al*., 2021). However, the various forms of land use and occupation, especially when carried out without prior knowledge of soil conditions, raise environmental concerns at local and regional scales (Alho *et al*., 2014).

In the Amazon biome, the replacement of native vegetation by the expansion of agricultural, livestock, and forestry activities has led to a significant imbalance in biodiversity. As a result, the loss of these areas not only contributes to increased deforestation but also directly compromises the preservation of natural resources, particularly through soil degradation (Enck *et al*., 2020; Lima *et al*., 2021).

Continuous changes in natural vegetation and the indiscriminate use of soil alter nutrient cycling, leading to losses in soil organic matter content and, consequently, changes in soil physical properties, particularly soil structure, with reductions in porosity and increases in soil bulk density (Gomes *et al*., 2020; Lima *et al*., 2021). These changes also affect drainage capacity, which constitutes an important indicator in the assessment of soil physical quality, as it is sensitive to management practices (Cunha Neto *et al*., 2018).

However, given the high heterogeneity of Amazonian environments, few studies have addressed the dynamics of soil physical attributes in forest plantations, such as Brazil nut (*Bertholletia excelsa* Bonpl.), particularly in the central region of the state (Maia *et al*., 2009; Moraes *et al*., 1996). Therefore, understanding these dynamics in Brazil nut production systems is essential to support sustainable production models that integrate economic, social, and environmental aspects.

Given the complexity of Amazonian environments and the changes in soil physical attributes resulting from land-use conversion, it is necessary to employ analytical tools capable of capturing the interaction among multiple variables. In this context, multivariate analysis techniques are essential for understanding changes in soil attributes, as they facilitate the interpretation of the behavior of these variables, support the development of more sustainable management practices, including forest management, and assist in distinguishing between adjacent environments (Jordão *et al*., 2022; Pantoja *et al*., 2019).

Although univariate methods are still widely used, multivariate analysis in soil science provides a more integrated and comprehensive view of the processes that govern the functioning of this component, and is therefore essential for understanding soil environments (Souza *et al*., 2020).

In light of the above, the present study aimed to evaluate soil physical attributes in a native forest area and in Brazil nut (*Bertholletia excelsa* Bonpl.) plantations in the Central Amazon, using descriptive and multivariate statistical analyses.

MATERIAL AND METHODS

Study area description and history

The study was conducted on a property owned by Agropecuária Aruanã S.A. (Aruanã Farm), located in the municipality of Itacoatiara, in the Middle Amazon mesoregion.

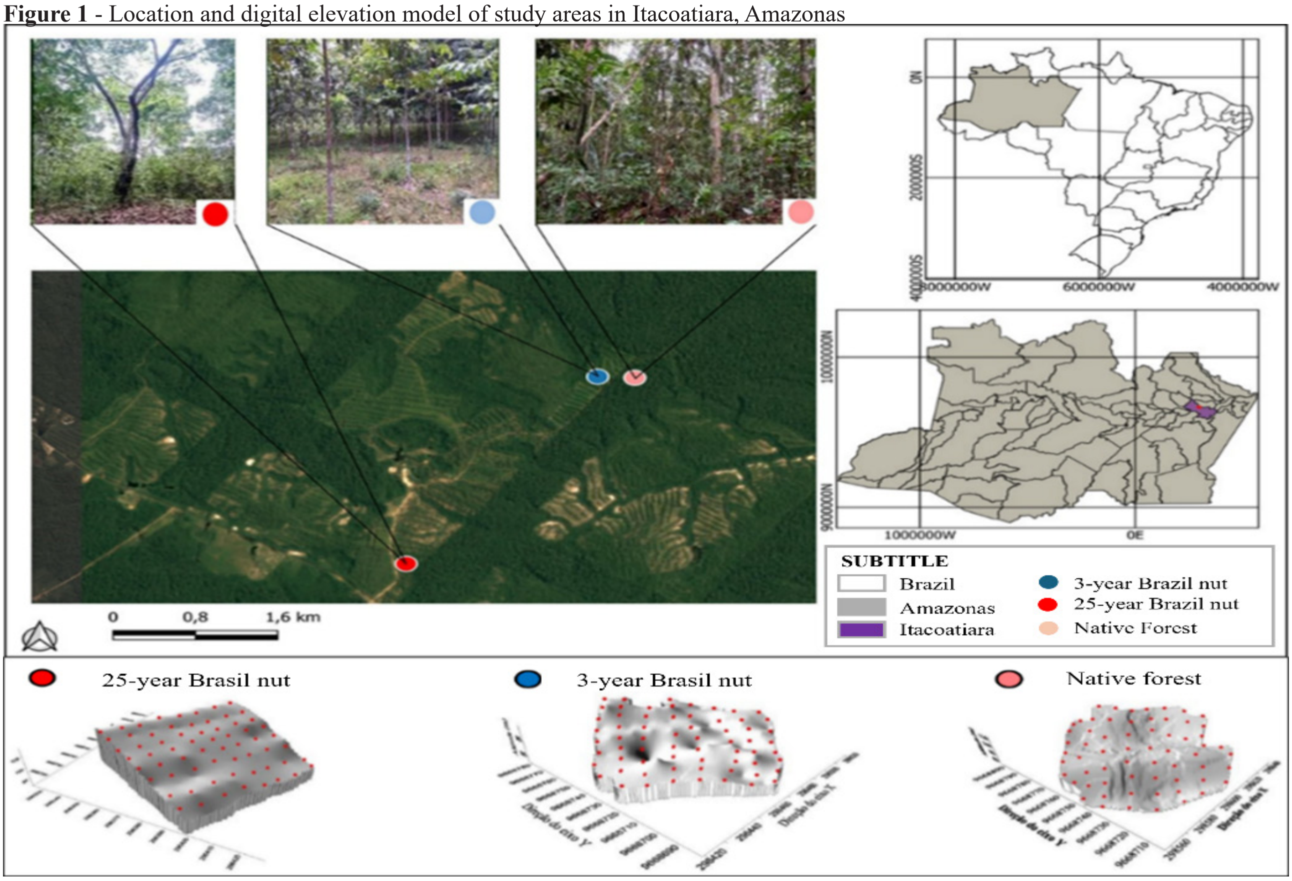
In this area, three environments were selected for the study: one area with natural characteristics (native forest-NF), used as a reference for comparison with anthropogenically managed environments, and two areas cultivated with Brazil nut trees of different ages (Figure 1), namely:

The native forest (NF) is located at the geographic coordinates 02°59′43.31″ S and 58°48′43.830″ W. Its natural characteristics remain intact, with vegetation composed of dense, multi-stratified tree cover, including species from the Lauraceae, Fabaceae, and Meliaceae families.

The 3-year-old Brazil nut plantation (CA3) is located at the geographic coordinates 02°59′43.79″ S and 58°48′47.90″ W. This area was originally native forest, later cleared and burned for land preparation, and subsequently used for pasture establishment between 1970 and 1973. However, due to pasture degradation and low agricultural productivity, the company adopted more sustainable and economically viable production systems. Currently, the CA3 area has been under a homogeneous Brazil nut plantation for over three years, with a spacing of 3 × 3 m (1,111 trees per hectare) and weed control carried out through semi-mechanized mowing.

The 25-year-old Brazil nut plantation (CA25), under cultivation for more than 25 years, is located at the geographic coordinates 03°01′20.64″ S and 58°49′55.23″ W. This area was also originally native forest that was cleared and burned for land preparation and is currently managed with a spacing of 15 × 15 m and intensive fruit harvesting. Since the plantation establishment, no fertilization or liming has been applied, and vegetation control has been carried out with a motorized brush cutter. More recently (approximately 4 years ago), the area received a new, denser planting of Brazil nut trees beneath the canopy of the older trees, aimed at increased fruit production.

Figure 1 - Location and digital elevation model of study areas in Itacoatiara, Amazonas



The soil in the study areas is classified as a *Latossolo Amarelo Distrófico* with a clayey texture (Silva; Rodrigues, 2003). According to the Köppen climate classification, as described by Alvares *et al.* (2014), the regional climate is classified as humid tropical climate (Af), with annual precipitation exceeding 2,000 mm and an average annual temperature of 27 °C, characterized by a short dry season and relative air humidity ranging from 80 to 85% (Silva; Rodrigues, 2003).

Field methodology

For each environment, a 70 m × 70 m sampling grid was established, with soil samples collected at grid intersections with 10 m spacing, for a total of 64 sampling locations. These points were georeferenced using GPS to generate a Digital Elevation Model (DEM).

Subsequently, disturbed soil samples were collected for particle-size (texture) characterization (Table 1) and determination of soil aggregate stability in each studied environment. In addition, undisturbed samples were collected using Uhland core rings (5 cm in height and 4 cm in internal diameter) in the 0 – 20 cm, 20 - 40 cm, and 40 - 60 cm layers to determine soil bulk density, soil penetration resistance, and macroporosity, microporosity, and total porosity, totaling 192 samples per area.

Laboratory methodology

The disturbed soil samples were air-dried in the shade, manually disaggregated, and passed through a set of sieves with 9.45 mm openings, separating the material retained on the 4.75 mm sieve for aggregate size distribution analysis, which was performed only on samples from the 0 - 20 cm layer. The material passing through the 2 mm sieve was used for particle-size (granulometric) analysis.

Aggregate stability was determined using the wet-sieving method, as described by Kemper and Rosenau (1986). The samples were placed on a set of sieves with mesh sizes of 2.0, 1.0, 0.500, 0.250, and 0.106 mm and subjected to vertical oscillations for 15 minutes at a frequency of 32 oscillations per minute using a Yoder-type wet-sieving apparatus (MARCONI model). The material retained on each sieve was then oven-dried at 105 °C for 24 hours until constant weight was reached.

The results were expressed as the percentage of aggregates retained in each sieve class (> 2 mm, 2 – 1 mm, and < 1 mm), and the values of mean weight diameter (MWD), geometric mean diameter (GMD), and aggregate stability index (ASI) were subsequently calculated according to the following equations:

Table 1 - Soil particle-size fractions in areas of Native Forest (NF), 3-year Brazil nut plantation (CA3), and 25-year Brazil nut plantation (CA25)

Area	Depth (cm)	Sand	Silt	Clay
			g kg^{-1}	
Native Forest	0 - 20	69.00	220.93	710.07
	20 - 40	57.02	178.23	764.75
	40 - 60	54.35	114.10	831.55
3-year Brazil nut	0 - 20	74.13	242.52	683.35
	20 - 40	51.98	226.20	721.82
	40 - 60	49.79	151.41	798.80
25-year Brazil nut	0 - 20	91.23	233.04	675.73
	20 - 40	67.45	185.62	746.93
	40 - 60	57.89	122.48	819.63

$$MWD = \frac{\sum_{i=1}^{N} n_i D_i}{\sum n_i} \quad (1)$$

$$GMD = 10^{\frac{\sum_{i=1}^{N} n_i \log Di}{\sum n_i}} \quad (2)$$

$$ASI = \left(MS - wp1.00 - sand / MS - sand\right) x100 \quad (3)$$

Where: *ni* = percentage of aggregates retained on a given sieve; *Di* = mean diameter of a given sieve; *N* = number of sieve size classes. *MS* = dry mass of the sample (g); *wp* 1.00 = mass of aggregates in the < 1.00 mm class (g).

Particle-size analysis was performed using the pipette method, employing a 0.1 mol L^{-1} NaOH solution as a chemical dispersant and slow mechanical agitation for 16 hours at 50 rpm using a mechanical shaker. The clay fraction was separated by sedimentation, the sand fraction by sieving, and the silt fraction was calculated by difference (Teixeira *et al*., 2017). The results are presented in Table 1.

For the determination of soil bulk density (Bd), soil penetration resistance (PR), and soil porosity, the samples contained in the volumetric rings were initially prepared by removing excess soil from their edges, followed by saturation in a plastic tray through the gradual rise of a water layer until reaching two-thirds of the ring height. Subsequently, the samples were weighed and placed on a tension table to determine microporosity (Mi), where they were subjected to a tension of −0.006 MPa (Teixeira *et al*., 2017).

After reaching equilibrium, the samples were weighed again to determine moisture content. Soil penetration resistance (PR) was then measured using a bench-top static penetrometer (model MA-933, Marconi), operated at a constant speed of 0.1667 mm s^{-1}, with a cone tip base diameter of 4 mm, as described by Serafim *et al*. (2008). Subsequently, the samples were oven-dried at 105 °C to determine bulk density (Bd) and total porosity (TP) using the core (volumetric ring) method. Macroporosity (Ma) was obtained as the difference between total porosity (TP) and microporosity (Mi).

Statistical analysis

The data were initially evaluated using exploratory descriptive statistical analysis, including calculation of the mean, coefficient of variation, and a normality test. A univariate analysis of variance (ANOVA) was performed to assess differences using the F-test; when significant, the means of the attributes were compared using Tukey's test at the 5% significance level.

The normality of the data within each environment was tested using the Kolmogorov–Smirnov (KS) test in STATISTICA® software, version 7.0 (Statsoft, 2004). The coefficient of variation (CV%) was evaluated according to the criteria proposed by Warrick and Nielsen (1980), who classify CV as low (CV < 12%), moderate (12 < CV < 60%), and high (CV > 60%).

For the principal component analysis (PCA), the data were stratified by layer, and the set of soil attributes with specific properties was standardized prior to analysis using the STATISTICA® software, version 7.0 (Statsoft, 2004). The principal components selected for interpretation included those that explained at least 70% of the total data variance (Cunha *et al*., 2019).

RESULTS AND DISCUSSION

Descriptive statistics

Descriptive statistics for the soil physical attributes are presented in Tables 2 and 3. The results of the Kolmogorov–Smirnov test indicated normality for most variables, suggesting that the presence of outliers in the dataset was not sufficient to distort the measures of central tendency (Souza *et al*., 2024).

Table 2 - Descriptive statistics and mean comparison test for the physical attributes in areas of Native Forest (NF), 3-year Brazil nut plantation (CA3), and 25-year Brazil nut plantation (CA25), on the three evaluated soil layers (0 - 20, 20 - 40 and 40 - 60 cm)

	Bd	Ma	Mi	TP	PR	Bd	Ma	Mi	TP	PR	Bd	Ma	Mi	TP	PR
	g cm^{-3}	m^{3}m^{-3}			MPa	g cm^{-3}	m^3 m^{-3}			MPa	g cm^{-3}	m^3 m^{-3}			MPa
	0 - 20 cm					20 - 40 cm					40 - 60 cm				
Native Forest															
Mean	1.15 b	0.14 a	0.45 b	0.60 a	1.49 b	1.26 ab	0.11 a	0.46 a	0.58 a	2.02 a	1.20 b	0.12 a	0.45 b	0.57 a	1.56 b
CV%	9.56	28.57	8.89	6.67	58.39	6.35	36. 36	6.52	5.17	43.56	15.83	33.33	17.77	17.54	51.92
K-S	0.08*	0.13*	0.08*	0.13*	0.15*	0.11*	0.07*	0.11*	0.08*	0.11*	0.16*	0.13*	0.22*	0.28*	0.13*
3 - year Brazil nut															
Mean	1.31 a	0.08 b	0.47 b	0.56 b	2.35 a	1.28 a	0.08 b	0.46 a	0.54 b	2.03 a	1.26 a	0.09 b	0.46 ab	0.56 a	1.85 a
CV%	6.11	25	6.38	5.36	42.68	18.75	37.50	19.56	18.52	47.78	7.14	33.33	6.52	5.36	40.54
K-S	0.08*	0.11*	0.12*	0.17*	0.07*	0.30*	0.09*	0.31*	0.37*	0.13*	0.07*	0.10*	0.06*	0.08*	0.12*
25-year Brazil nut															
Mean	1.10 c	0.08 b	0.49 a	0.58 a	1.69 b	1.21 b	0.07 b	0.48 a	0.55 b	1.98 a	1.19 b	0.09.b	0.48 a	0.57 a	1.79 ab
CV%	4.54	50.00	6.12	6.90	21.30	4.13	28.57	4.17	5.45	19.70	4.20	33.33	4.17	5.26	21.79
K-S	0.09*	0.22*	0.05*	0.16*	0.08*	0.10*	0.17*	0.11*	0.08*	0.06*	0.07*	0.06*	0.07*	0.10*	0.11*
Test F	109.41*	47.76*	18.60*	15.95*	22.78*	37.09*	36.45*	2.74^{ns}	14.04*	0.33^{ns}	8.82*	13.06*	5.14*	1.65^{ns}	3.05*

CV: coefficient of variation; K–S: Kolmogorov–Smirnov normality test. * Significant at the 5% probability level; Bd: soil bulk density; Ma: macroporosity; Mi: microporosity; TP: total porosity; PR: soil penetration resistance; F: F-test; ns: not significant. Means followed by the same lowercase letter in the column within each soil layer do not differ (Tukey p < 0.05)

Table 3 - Descriptive statistics and mean comparison test for aggregate stability at a depth of 0 - 20 cm in in areas of Native Forest (NF), 3-year Brazil nut plantation (CA3), and 25-year Brazil nut plantation (CA25)

Parameters		GMD	MWD	ASI	> 2.00 mm	2 - 1 mm	< 1.00 mm
		------------ mm ------------		------------------------------ % ------------------------------			
		0 - 20 cm					
Native Forest	Mean	2.10 b	2.85 b	90.75 b	81.18 b	3.92 a	14.96 a
	CV%	25.24	7.37	7.91	8.22	65.56	42.04
	K-S	0.08*	0.10*	0.17*	0.06*	0.09*	0.10*
3-year Brazil nut	Mean	2.21 b	2.89 b	91.90 b	82.39 b	4.26 a	14.67 a
	CV%	33.94	14.19	13.66	15.55	54.46	70.21
	K-S	0.06*	0.11*	0.16*	0.11*	0.08*	0.11*
25-year Brazil nut	Mean	2.65 a	3.11 a	95.88 a	90.31 a	2.22 b	7.47 b
	CV%	8.68	2.57	2.54	3.43	45.04	34.00
	K-S	0.11*	0.11*	0.13*	0.11*	0.14*	0.11*
	F	23.18*	23.98*	10.72*	22.71*	16.74*	22.22*

CV: coefficient of variation (%); K–S: Kolmogorov–Smirnov normality test. * Significant at the 5% probability level; GMD: geometric mean diameter; MWD: mean weight diameter; ASI: aggregate stability index; ns: not significant. Means followed by the same lowercase letter in the column within each soil layer do not differ (Tukey p < 0.05)

Most attributes exhibited CV% values ranging from low to moderate, consistent with Warrick and Nielsen (1980) and Cunha *et al*. (2017), who reported low to moderate CV% variability when evaluating soil physical attributes in the Amazon region. Exceptions were observed for the aggregate classes 2 - 1 mm and < 1.00 mm in the NF and CA3 areas (Table 3), where high CV% values reflect data heterogeneity.

This variation may be attributed to the greater variability inherent to the analysis, since several factors can influence aggregate stability values, including uneven organic matter content among samples, variations in sand, silt, and clay fractions, as well as differences in soil bulk density, porosity, and microclimatic conditions in the study area. Consequently, these factors tend to have a greater impact on the smaller aggregate size classes, which are naturally more sensitive to such variations.

Based on the analysis of variance using the Tukey test ($p < 0.05$), it was observed that in the 0 - 20 cm layer (Table 2), bulk density (Bd) was slightly higher in the CA3 area (1.31 g cm^{-3}) compared to NF (1.15 g cm^{-3}) and CA25 (1.10 g cm^{-3}). This likely occurred because, in CA3, the history of pasture use led to soil compaction from animal trampling, reducing pore space and increasing soil mass per unit volume. According to Carmo *et al*. (2018), pasture systems exhibit physical vulnerability, making soils more prone to compaction and, consequently, more susceptible to erosive processes. In addition, the three-year establishment period of CA3 may not have been sufficient to promote recovery or significant changes in soil attributes.

On the other hand, the favorable bulk density (Bd) conditions observed in CA25 are likely associated with the 25-year cultivation period and the absence of soil disturbance in this system, which contributes to the stability of soil structure (Calonego *et al*., 2012). In addition, the continuous input of plant residues from annual maintenance operations increases soil organic matter content, which positively affects physical attributes, such as reducing bulk density. In the native forest (NF) environment, this result is expected due to the absence of anthropogenic activities.

When bulk density (Bd) was evaluated in the 20 - 40 and 40 - 60 cm layers (Table 2), it was observed that at 20 - 40 cm, the cultivated areas CA3 (1.28 g cm^{-3}) and CA25 (1.21 g cm^{-3}) differed statistically from each other but did not differ from NF (1.26 g cm^{-3}). In the 40 - 60 cm layer, CA3 differed statistically from NF and CA25, showing a higher Bd value (1.26 g cm^{-3}). Despite this, these values remain below the critical threshold for root growth in clayey soils (1.45 g cm^{-3}) (Reichert; Reinert; Braida, 2003) and are therefore considered adequate for Brazil nut development.

Regarding penetration resistance (PR), significant differences were observed among environments and layers (Table 2). In the 0 - 20 cm layer, the soil under CA3 exhibited the highest PR value (2.35 MPa), differing statistically from NF (1.49 MPa) and CA25 (1.69 MPa), which were similar to each other. No differences were detected among areas in the 20 - 40 cm layer. In the 40 - 60 cm layer, only CA3 (1.85 MPa) differed from NF (1.56 MPa), whereas CA25 (1.79 MPa) showed values similar to those in the other environments.

The higher PR values observed in the CA3 area in all layers are likely associated with the higher bulk density (Bd), as these two attributes are directly related (Oliveira *et al*., 2024a). The removal of vegetation cover may also explain these results, as well as the history of animal trampling and the relatively short crop establishment period (three years). However, considering the critical threshold of 2.5 MPa for clayey soils established by Sene *et al*. (1985), all environments in their respective layers had PR values below this limit, indicating that root growth was not restricted.

The results for macroporosity (Ma) indicate that, in all layers, the native forest (NF) exhibited higher values (0.14 to 0.12 $m^3 m^{-3}$) compared to CA3 (0.08 to 0.09 $m^3 m^{-3}$) and CA25 (0.08 to 0.09 $m^3 m^{-3}$). This can be attributed to the natural environment, which is free of anthropogenic disturbance, as reflected in the bulk density (Bd). On the other hand, in the areas cultivated with CA3 and CA25, the lower Ma values may be limiting for adequate plant growth, as they fall below 0.10 $m^3 m^{-3}$, a threshold considered limiting for root development (Kiehl, 1979). This indicates that, in both CA3 and CA25 areas, macroporosity may compromise oxygen diffusion, reduce soil aeration capacity, and limit normal root respiration (Oliveira *et al*., 2024b).

Possible explanations for these atypical Ma values in the cultivated areas include animal grazing observed in CA3, the long-term, intensive use of CA25 (25 years), and machinery traffic associated with maintenance operations in both areas. These factors likely led to soil compaction, increasing bulk density (Bd) and consequently reducing macroporosity (Ma), given the inverse relationship between these attributes.

Higher values of total porosity (TP) were observed for NF and CA25 in the 0 - 20 cm layer, indicating that CA25 reached porosity levels comparable to those without anthropogenic disturbance after 25 years of forest plantation establishment (Table 2). The reduction in TP in the 0 - 20 cm layer of CA3 and in the 20 - 40 cm layer of the cultivated areas may reflect the decrease in macroporosity (Ma), since several studies indicate that microporosity (Mi) does not vary substantially with soil layer and is not significantly influenced by soil management (Giarola *et al*., 2009). Nevertheless, these values are above 0.50 $m^3 m^{-3}$, which is considered an ideal porosity threshold for maintaining soil physical quality (Silva; Cezar; Nóbrega, 2012). In the 40–60 cm layer, no statistical differences were observed, indicating that physical changes occur mainly in the surface soil layers.

When analyzing variables related to soil aggregate stability in the 0 - 20 cm layer (Table 3), the highest values followed the sequence CA25 > NF > CA3. This indicates that, although CA25 is a cultivated area, it exhibits better soil aggregation, likely associated with greater litter input. According to Silva, Reinert, and Reichert (2000), this increases soil organic matter content and, consequently, enhances soil aggregation.

The aggregation results may also be explained by the management practices adopted in the CA25 area. In addition to the Brazil nut plantation established 25 years ago, the area recently (approximately four years ago) received a new, denser planting of Brazil nut trees under the canopy of the older trees, aimed at fruit production. This increased planting density promotes greater litter production, thereby improving soil aggregation.

Multivariate analysis

In the principal component analysis (PCA), the number of extracted components was defined to explain at least 70% of the total variance. This threshold represents, graphically, the discriminating power of soil attributes in each studied environment and the contribution of each variable to the total variance (Hair *et al*., 2005).

From this perspective, the first and second principal components were sufficient to explain the total variance (greater than 70%), justifying their use. However, the 40 - 60 cm layer, under the soil conditions studied, may not adequately represent the physical properties for characterizing and discriminating among environments (Table 4).

The surface layer (0 - 20 cm) revealed significant differences among the NF, CA3, and CA25 areas. The attributes most strongly correlated with the forest environment in this layer were macroporosity (Ma) and total porosity (TP) (Figure 2A). This result may be attributed to the absence of anthropogenic disturbance and the greater species diversity, which promotes higher inputs of plant residues and, consequently, increased soil organic matter content (Freitas *et al*., 2014), enhanced biological activity, and greater pore formation.

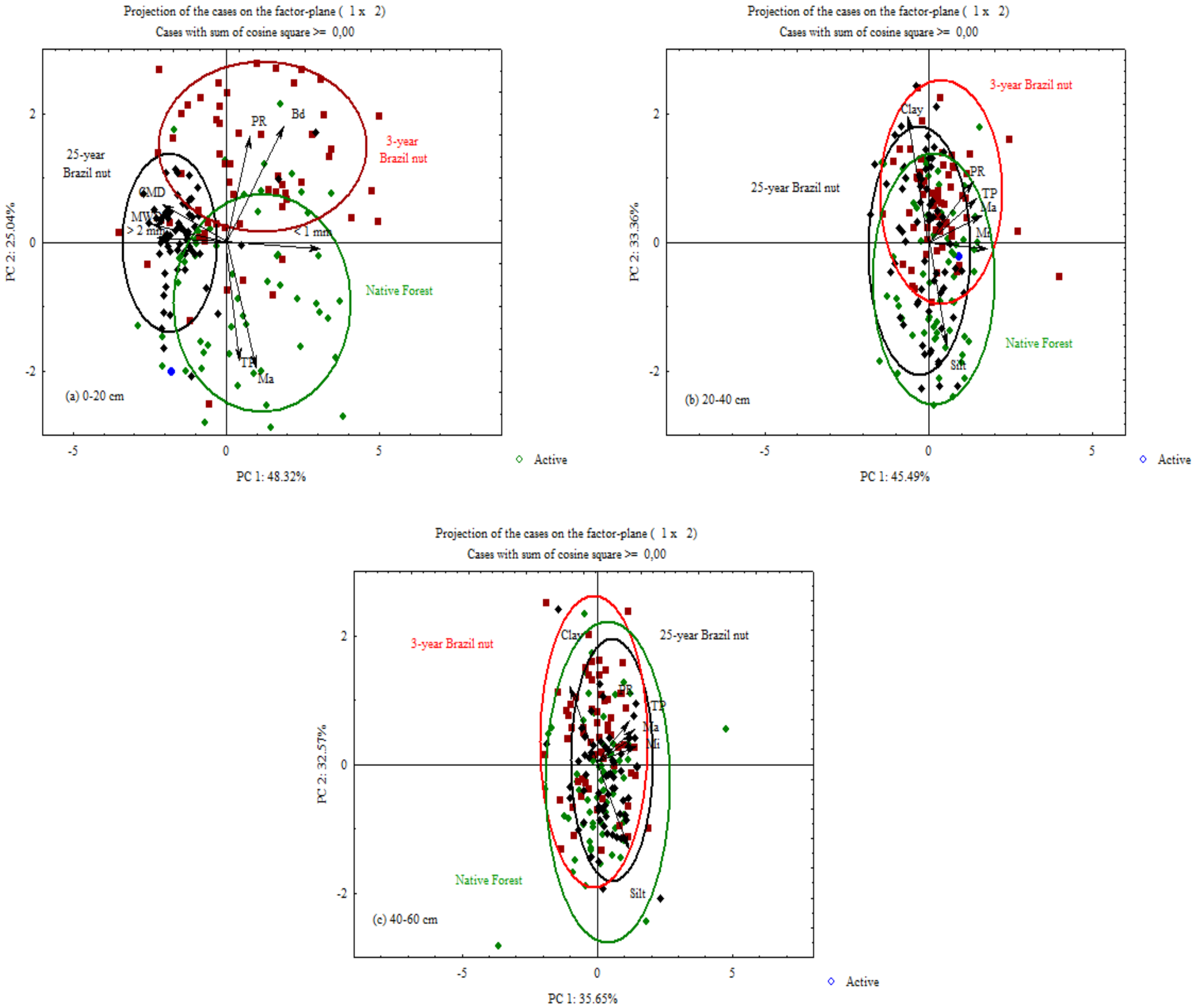
On the other hand, the CA25 area showed a greater influence of soil aggregation variables (GMD, MWD, and aggregates > 2.00 mm), whereas in CA3, variables related to soil compaction (Bd and PR) were responsible for characterizing this environment (Figure 2A). These results indicate that, in CA25, the duration of cultivation and the management practices adopted favor the accumulation of organic matter at the soil surface, positively influencing soil structure and making it more similar to a natural environment, an effect not observed in CA3.

Table 4 - Contribution of principal components (PC1 and PC2) of physical attributes in a Native Forest environment (NF), 3-year Brazil nut plantation (CA3), and 25-year Brazil nut plantation (CA25), on the three evaluated soil layers (0 - 20, 20 - 40 and 40 - 60 cm)

Attributes	0 - 20 cm		20 - 40 cm		40 - 60 cm	
	PC1	PC2	PC1	PC2	PC1	PC2
Sand	-	-	-	-	-	-
Silt	-	-	0.26	16.01	4.59	11.92
Clay	-	-	0.26	16.08	4.64	11.89
Ma	0.19	7.72	14.76	0.01	10.42	3.03
Mi	0.32	1.12	12.70	0.02	8.11	1.62
TP	0.00	4.77	13.24	0.43	6.10	2.35
Bd	0.80	5.91	-	-	-	-
PR	0.19	5.45	4.27	0.82	1.80	1.77
GMD	9.14	0.04	-	-	-	-
MWD	9.86	0.00	-	-	-	-
ASI	8.75	0.01	-	-	-	-
> 2 mm	9.25	0.00	-	-	-	-
< 1 mm	9.82	0.01	-	-	-	-
Variance Accumulate (%)	48.32	25.04	45.49	33.36	35.65	32.57
Variance explained (%)	73.36	78.85	68.22			

Ma: macroporosity; Mi: microporosity TP: total porosity; Bd: soil bulk density; PR: soil penetration resistance; GMD: geometric mean diameter; MWD: mean weight diameter; ASI: aggregate stability index

Figure 2 - Principal component analysis of physical attributes evaluated in soils under a Native Forest (NF), 3-year Brazil nut plantation (CA3), and 25-year Brazil nut plantation (CA25), on the three evaluated soil layers (0 - 20, 20 - 40 and 40 - 60 cm)



PC1: Principal Component 1; PC2: Principal Component 2; A: Depth of 0 - 20 cm; B: Depth of 20 - 40 cm; C: Depth of 40 - 60 cm

The observed results in the CA3 area may be explained by its previous grazing land use and the resulting soil degradation. In contrast, the relatively recent establishment of the Brazil nut plantation has not yet promoted the conditions necessary for soil decompaction in this environment. Studies indicate that increases in bulk density (Bd) are associated with reductions in total porosity (TP), mainly due to decreases in macroporosity (Ma), which, in turn, lead to increased penetration resistance (PR) (Sabino *et al*., 2022). These factors negatively affect soil water infiltration rates (Cunha Neto *et al*., 2018).

When the subsurface layer (20 - 40 cm) was evaluated (Figure 2B), the environments did not differ from one another, with the point clouds overlapping across the studied areas. A similar pattern was observed in the 40 - 60 cm layer (Figure 2C), indicating low variability among environments with increasing depth. This pattern suggests that the factors affecting soil physical quality act predominantly in the surface layer.

CONCLUSIONS

1. The conversion of native forest to pasture and subsequently to CA3 cultivation increased soil penetration resistance (PR = 2.35 MPa) and soil bulk density (Bd = 1.31 g cm^{-3}) in the upper 0 - 20 cm layer.

2. The highest values of macroporosity (Ma = 0.14 m^3 m^{-3}) and total porosity (TP = 0.60 m^3 m^{-3}) were observed in the surface layer of the native forest (NF).
3. The CA25 area is distinguished by lower bulk density (Bd) in all layers and greater soil aggregation, as indicated by the geometric mean diameter and mean weight diameter (GMD = 2.65 mm; MWD = 3.11 mm), as well as by the aggregate stability index (ASI = 95.88%) and aggregates > 2.00 mm (90.31%).
4. Based on principal component analysis, soil aggregation and porosity are the main attributes responsible for distinguishing the CA3 Brazil nut area from the other areas in the surface soil layer.

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DATA AVAILABILITY STATEMENT

Data-available-upon-request to the corresponding author.

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