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Scientific Article

Soil attributes as environmental indicators in a private natural heritage reserve in the Brazilian semi-arid region

Atributos dos solos como indicadores ambientais em reserva particular do patrimônio natural no semiárido brasileiro

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ABSTRACT – The Brazilian semi-arid region has unique characteristics that, when associated with degrading anthropogenic activities, such as wildfires and deforestation, intensify environmental degradation processes. In this context, the implementation and management of protected areas are fundamental strategies for ecosystem protection and restoration, with the Private Natural Heritage Reserve (PNHR) standing out. This study aimed to physically and chemically characterize the soil of three areas with different land uses and land covers at the Não Me Deixes Farm and the Não Me Deixes PNHR: native forest (NF), regenerating area (RA), and agricultural area (AA). In each area, five disturbed samples were collected from the 0–20 cm layer to determine particle-size distribution and soil chemical attributes (total organic carbon - TOC, total nitrogen - N, pH, electrical conductivity - EC, phosphorus - P, sodium - Na, potassium - K, calcium - Ca, magnesium - Mg, and potential acidity), and three undisturbed samples were collected from the 0–10 cm layer to determine soil bulk density (BD). The data were subjected to multivariate statistical analyses to evaluate differences among the areas. AA had the highest BD and the lowest TOC content (27.70 g kg^{-1}), indicating greater soil quality degradation, whereas NF and RA showed 66.28 and 62.89 g kg^{-1}, respectively. RA exhibited attributes similar to those of NF, differing significantly from AA. It was concluded that the PNHR proved to be an important instrument for the restoration of degraded areas and the conservation of soil quality, showing better edaphic conditions.

Keywords: Conservation unit. Environmental degradation. Total organic carbon.

RESUMO – O semiárido brasileiro apresenta características singulares que, associadas a ações antrópicas degradadoras, como queimadas e desmatamento, intensificam os processos de degradação ambiental. Nesse contexto, a implementação e gestão de unidades de conservação são estratégias fundamentais para a proteção e recuperação dos ecossistemas, destacando-se a Reserva Particular do Patrimônio Natural (RPPN). Objetivou-se caracterizar físico-quimicamente o solo de três áreas com diferentes usos e ocupações da Fazenda Não Me Deixes e da RPPN Não Me Deixes: mata nativa (MN), área em regeneração (AR) e agricultura (AG). Em cada área foram coletadas cinco amostras deformadas na camada de 0-20 cm para determinação da granulometria e atributos químicos do solo (carbono orgânico total - COT, nitrogênio total - N, pH, condutividade elétrica - CE, fósforo - P, sódio - Na, potássio - K, cálcio - Ca, magnésio - Mg e acidez potencial), e três amostras indeformadas na camada de 0-10 cm para a determinação da densidade do solo (Ds). Os dados foram submetidos a análises estatísticas multivariadas para avaliar diferenças entre as áreas. A AG apresentou maior Ds e menor teor de COT (27,70 g kg^{-1}), indicando maior degradação da qualidade do solo, enquanto MN e AR apresentaram 66,28 e 62,89 g kg^{-1}, respectivamente. A AR apresentou atributos semelhantes aos da MN, diferindo significativamente da AG. Conclui-se que a RPPN se mostrou um importante instrumento na recuperação de áreas degradadas e na conservação da qualidade do solo, apresentando melhores condições edáficas.

Palavras-chave: Unidade de conservação. Degradação ambiental. Carbono orgânico total.

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INTRODUCTION

The Brazilian semi-arid region, considered one of the most populated in the world and where most people have agropastoral activities as a source of income, is characterized by a rainfall regime marked by irregularity, high temperatures and high rates of insolation and evaporation (MEDEIROS; CESÁRIO; MAIA, 2023). Inadequate land use, as observed in conventional agricultural systems, when associated with the climatic conditions mentioned, has intensified environmental degradation (ANDRADE et al., 2020).

The typical vegetation is Caatinga, adapted to climatic seasonality and high temperatures, being considered one of the largest and richest Seasonally Dry Tropical Forests (SDTF), with more than 11 thousand plant species cataloged (INSA, 2026; SOUZA et al., 2019). However, a large part of its area has already been converted due to anthropogenic actions (SOUZA et al., 2019).

Given this scenario, it is also important to emphasize that, even in the face of its importance, less than 10% of the Caatinga extension is protected (PAIVA et al., 2021). In this context, the implementation of conservation areas plays an essential role in mitigating degradation, reducing deforestation, favoring forest restoration and, consequently, promoting soil conservation, reducing erosive processes, limiting land use and occupation, and protecting ecosystem functions

(MENDES et al., 2018).

The Conservation Units (CUs), provided for in the National System of Conservation Units (*Sistema Nacional de Unidades de Conservação* - SNUC), defined as areas with relevant natural characteristics, are fundamental instruments to protect endangered species, natural landscapes, geological and geomorphological characteristics, recover and restore degraded ecosystems, and promote environmental education (BRASIL, 2000).

The categories of CUs particularly include the Private Natural Heritage Reserve (PNHR), an area of private domain and permanent character, with great potential to assist in the conservation of the Caatinga, as it can only be used for research, conservation, education and ecotourism purposes (SILVA; PINTO; SCARANO, 2021). Studies show that, when analyzing rural properties in different biomes, such as the Atlantic Forest, Cerrado, and Caatinga, with and without PNHRs, those with the CU showed significantly higher rates of natural vegetation (NASCIBEM et al., 2023).

Despite the importance of these CUs, research studies conducted in PNHRs in the Brazilian semi-arid region focus mainly on aspects related to public policies, biodiversity of fauna and flora, and climatic characterization of these areas. On the other hand, there are still few studies evaluating the physicochemical attributes of soils in this CU category, which limits the understanding of the role of PNHRs in the maintenance and conservation of soil quality.

Thus, it was hypothesized that the implementation and management of a CU favor the regeneration and restoration process of degraded areas, besides promoting the increase of the total organic carbon content, significantly altering the physicochemical parameters of the soil. Therefore, the objective of this study was to perform the physicochemical characterization of the soil in areas with different uses and occupations (native forest, regenerating area and agriculture), in order to evaluate the influence of a PNHR on the maintenance of edaphic properties.

MATERIAL AND METHODS

The study area includes the Não me Deixes Farm and the Não Me Deixes PNHR (Figure 1), located in the municipality of Quixadá, Ceará, approximately 140 km away from the state capital, Brazil. Quixadá has the geographic coordinates 4°58’17” S and 39°00’55” W and is part of the micro-region known as “Sertões de Quixeramobim”, in the central region of the state (IPECE, 2017). Figure 1 shows the location of the study area.

The Quixadá region is marked by the Hot Semi-Arid climate (Köppen-Geiger BSh), has an average annual rainfall of 765 mm, a rainy season concentrated from February to April, and an average temperature of 26 to 28 ºC (ANDRADE et al., 2020; IPECE, 2017). The soil classes identified in the study area, according to the survey for medium-intensity recognition of soils in the State of Ceará, carried out by the Ceará Foundation of Meteorology and Water Resources (FUNCEME, 2024), were *Argissolo Vermelho* (Ultisol) and *Neossolo litólico* (Entisol), as presented in Figure 2.

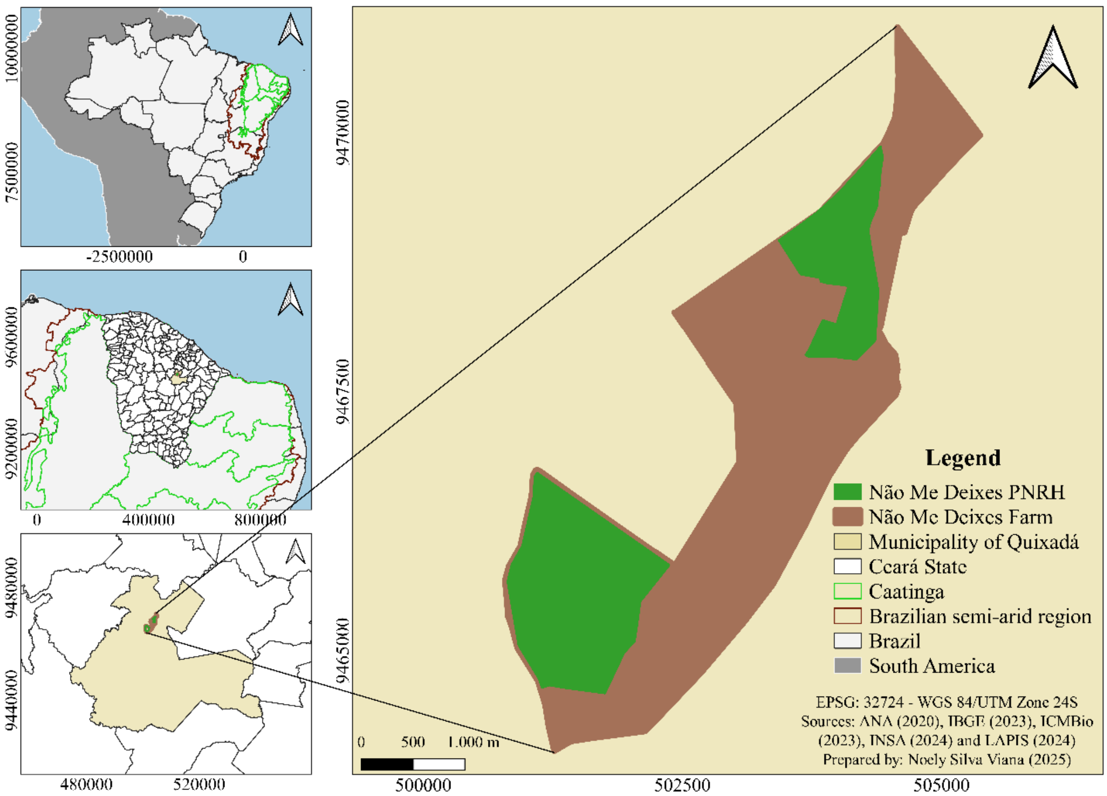


Figure 1. Location map of the Não Me Deixes Farm and PNHR, Quixadá, State of Ceará, Brazil.

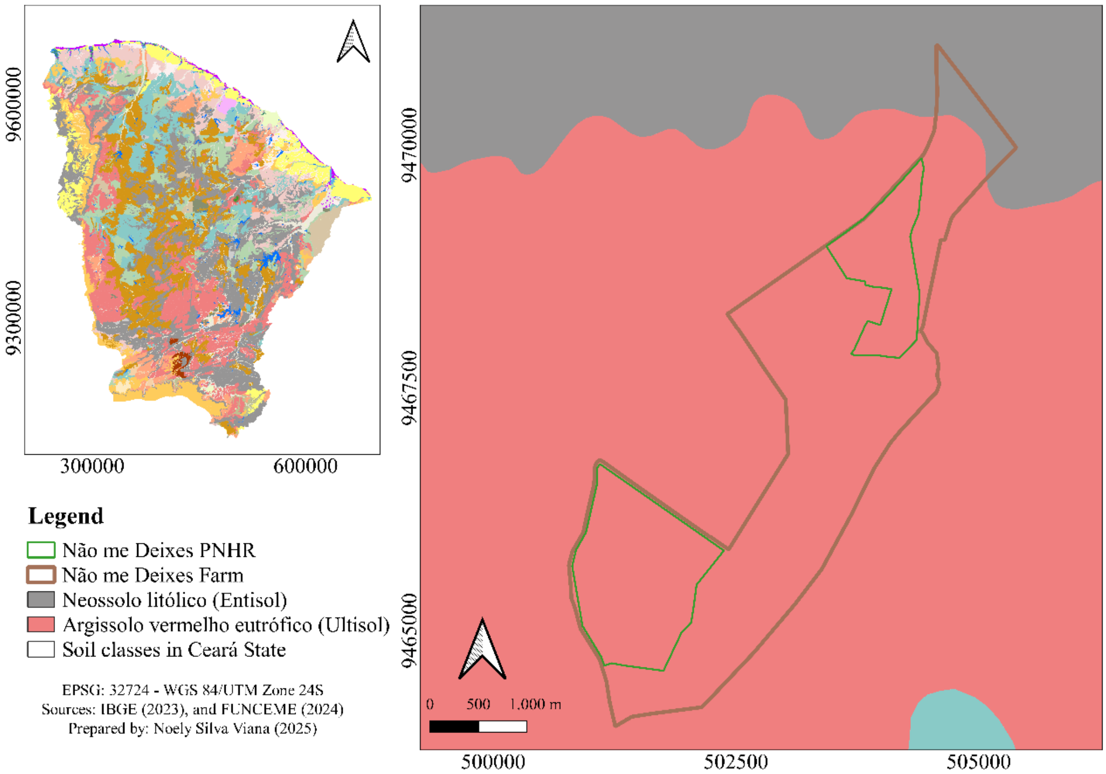


Figure 2. Soil map of the Não Me Deixes Farm and PNHR, Quixadá, State of Ceará, Brazil.

The predominant soil class in the PNHR and at the farm is *Argissolo vermelho eutrófico* (Ultisol). *Argissolos* (Ultisols) are usually deep, with good drainage and without impediments to mechanization when they are located in less rugged reliefs with no stoniness. In addition, when eutrophic, they are considered to have medium to high fertility (FUNCEME, 2024).

The other class identified, but in a much smaller proportion, was *Neossolo litólico* (Entisol). These soils can be defined as shallow, usually associated with stoniness and rockiness, and restrictions for agricultural use. In most cases, they are used for pasture and/or subsistence crops, but are indicated for environmental preservation (FUNCEME, 2024).

For this study, three areas were selected: agricultural area (AA), regenerating area (RA) and native forest (NF). AA is an area within the farm, outside the limits of the PNHR, where the subsistence cultivation of maize and common bean has been carried out for approximately 25 years (Figure 3A). RA (Figure 3B), also located outside the PNHR, was subjected to reforestation actions in 2018, after the end of cattle raising activities on the farm. Finally, NF corresponds to an area of preserved native vegetation located within the PNHR (Figure 3C).

To obtain the physicochemical characterization of the soil, the study was conducted in a comparative design, considering the three areas: AA, RA and NF. The sampling points were distributed so as to represent the variability of each environment, avoiding trails and roads. Collections were carried out in May 2023. Five disturbed composite samples were collected in each area, at a 0–20 cm depth, using a Dutch auger, and each composite sample consisted of three single samples. In addition, three undisturbed samples were collected in each area, at a 0–10 cm depth, using an Uhland sampler. Disturbed samples were air-dried, pounded to break up clods and passed through a 2-mm-mesh sieve to obtain the Air-Dried Fine Earth (ADFE), used in the analyses.

Physicochemical analyses of soil bulk density (BD), total nitrogen (N), hydrogen potential (pH), electrical conductivity (EC), phosphorus (P), sodium (Na), potassium (K), potential acidity, aluminum (Al), calcium (Ca), magnesium (Mg), total organic carbon (TOC), particle size, sum of exchangeable bases (SB), Total Cation Exchange Capacity (CEC) and base saturation percentage (V) were performed, as described in Table 1.

The results obtained in the analyses were subjected to multivariate statistical analysis using the free software SAS® OnDemand for Academics. Initially, Principal Component Analysis (PCA) was performed to characterize the areas based on physicochemical attributes, then Multivariate Analysis of Variance (MANOVA) was applied to assess the multivariate difference between the areas, adopting a significance level of 5% ($p < 0.05$). Subsequently, Canonical Discriminant Function Analysis (CDA) was performed to check the discrimination between the areas. Finally, the means of the first canonical variable were compared using Tukey test, considering a significance level of 5% ($p < 0.05$).

Figure 3. Agricultural area (A) and regenerating area at the Não Me Deixes Farm (B) and native forest area at the Não Me Deixes PNHR (C).

Table 1. Physicochemical analyses performed on soil samples.

Attributes analyzed	Method used
BD (g cm^{-3})	Embrapa's Manual of Soil Analysis Methods (TEIXEIRA et al., 2017)
N (g kg^{-1})	
pH	
EC (μS cm^{-1})	
P (mg kg^{-1})	
Na (cmol$_c$/dm^3)	
K (cmol$_c$/dm^3)	
Potential acidity (cmol$_c$ kg^{-1})	
Al (cmol$_c$ kg^{-1})	
SB (cmol$_c$ kg^{-1})	
CEC (cmol$_c$ kg^{-1})	
V (%)	
Ca (cmol$_c$ kg^{-1})	Embrapa's Manual of Soil Analysis Methods (TEIXEIRA et al., 1997)
Mg (cmol$_c$ kg^{-1})	
TOC (g kg^{-1})	Mendonça and Matos (2005)
Particle-size analysis	Amaral Filho, Assis Júnior and Mota (2008)

RESULTS AND DISCUSSION

The mean values of the physicochemical analyses of the areas under study are presented in Table 2. According to the analysis of the structural physical attribute, BD values were higher in AA, reaching 1.60 g cm^{-3}, while RA and NF showed values of 1.48 and 1.45 g cm^{-3}, respectively (Table 2).

As bulk density is directly associated with soil structure, inadequate management can compromise this condition. Thus, the increase in BD negatively impacts crop development, since it reduces aeration, infiltration and water retention in the soil, compromising root growth (BRADY; WEIL, 2013).

On the other hand, the lower values observed in RA and NF may be related to greater vegetation cover, which favors the maintenance of organic matter, contributing to aggregate formation and stability (BRADY; WEIL, 2013).

Table 2. Mean values obtained in the physicochemical analyses of the variables according to the layers and areas.

Variables	Layer (cm)	NF	RA	AA
BD (g cm^{-3})	0 - 10	1.45	1.48	1.60
Textural classification	0 - 20	Sandy Loam	Loamy Sand	Sandy Loam
TOC (g kg^{-1})	0 - 20	66.28	62.89	27.70
N (g kg^{-1})	0 - 20	0.44	0.37	0.51
pH	0 - 20	5.39	5.84	5.84
EC (μS cm^{-1})	0 - 20	36.63	34.54	33.27
P (mg kg^{-1})	0 - 20	0.55	0.56	1.85
Na (cmol$_c$/dm^3)	0 - 20	0.005	0.004	0.006
K (cmol$_c$/dm^3)	0 - 20	0.013	0.014	0.016
Ca (cmol$_c$ kg^{-1})	0 - 20	1.78	1.56	1.80
Mg (cmol$_c$ kg^{-1})	0 - 20	0.54	0.68	1.58
Potential acidity (cmol$_c$ kg^{-1})	0 - 20	1.45	0.66	0.73
SB (cmol$_c$ kg^{-1})	0 - 20	2.34	2.26	3.40
T (cmol$_c$ kg^{-1})	0 - 20	3.79	2.92	4.13
V (%)	0 - 20	61.74	77.40	82.32

NF: native forest; RA: regenerating area; AA: agricultural area; SB: sum of exchangeable bases; T: Total cation exchange capacity; V%: base saturation percentage.

Particle-size analysis indicated a predominance of the sand fraction (70-80%) in all areas, with textural classification Sandy Loam for NF and AA, and Loamy Sand for RA. Soils with high sand fraction have lower organic matter content, reduced cation exchange capacity, high permeability, and low water retention capacity (SILVA et al., 2024; BRADY; WEIL, 2013).

Despite the predominance of the sand fraction in all areas, TOC contents showed a strong distinction between them, with values of 66.28 (NF), 62.89 (RA) and 27.70 g kg^{-1} (AA), highlighting that land use and management exert a greater influence on this attribute than texture. The NF > RA > AA pattern corroborates studies that point to higher TOC content in preserved areas, given that agricultural areas are impacted by fires and deforestation, favoring carbon loss (ANDRADE et al., 2020).

Thus, the conversion of native vegetation for agricultural purposes compromises the function of the forest as a carbon sink, and the reduction of TOC contents is an indication of land use intensification and soil quality degradation (ANDRADE et al., 2020). It is also worth pointing out that RA exhibited a value close to that of NF. This TOC content in RA can be associated with increased vegetation cover, which contributes to the deposition of organic matter in the soil (SILVA et al., 2024).

Considering that TOC plays a fundamental role in maintaining soil quality, influencing physical, chemical, and biological attributes, it is important to understand the effects of changes in land use on this attribute (SILVA et al., 2024). In this context, the results obtained indicate that the regeneration process has favored soil quality with regard to TOC.

N contents ranged from 0.37 to 0.51 g kg^{-1}, with a higher value in AA. Andrade et al. (2020) obtained total N contents for the semi-arid region in open Caatinga areas of 0.83 g kg^{-1} (0-10 cm) and 0.38 g kg^{-1} (10-20 cm), and in dense Caatinga areas of 0.75 g kg^{-1} (0-10 cm) and 0.28 g kg^{-1} (10-20 cm). These authors pointed out that low N contents, even in preserved areas, are linked to water deficit, low soil moisture and air humidity, and high temperatures (ANDRADE et al., 2020).

Although AA had the lowest TOC content, the area recorded the highest N content. This behavior may be related to biological N fixation through the common bean crop, a legume that performs a symbiotic association with bacteria called rhizobia, capable of fixing atmospheric N and converting it into a form assimilable by vegetation (KARAVIDAS et al., 2023; REINPRECHT et al., 2020). Thus, biological N fixation may have contributed to the increase of this attribute in the soil, culminating in a higher N content in AA.

Regarding pH, the values observed were 5.39 (NF) and 5.84 (RA and AA), so the soils were characterized as moderately acidic (ARAÚJO FILHO et al., 2022). Vasconcelos (2022) observed lower pH values in preserved areas, in agreement with the results found in the present study. As pointed out by the author, this behavior may be related to the increase in organic carbon over the years, whose greater availability favors the release of organic acids and, consequently, the increase in soil acidity.

In the EC analysis, the results obtained for NF, RA and AA were 36.63, 34.54 and 33.27 µS cm^{-1}, respectively. According to Brady and Weil (2013), none of the soils has high salinity, since even the most sensitive plants are affected when the EC values are close to 2 dS m^{-1}, which was not the case for the areas of the present study.

The P contents found were 0.55, 0.56 and 1.85 mg kg^{-1} for NF, RA and AA, respectively, with the highest value observed in AA. Studies point to higher values in agricultural areas when compared to pasture and reforestation areas, resulting from the application of fertilizers (GAVA et al., 2022). In this context, the higher P content observed in AA may be associated with the management of this area over the last few years. However, in relation to fertility, the P contents are low for all areas (AQUINO et al., 1993).

Na and K contents were low and similar in all three areas. Since Na contents are low, they do not limit plant growth, as they have no effect on soil structure (BRADY; WEIL, 2013). In relation to K, its dynamics in the soil are mainly influenced by cation exchange and, due to its high mobility, this nutrient can be easily leached (BRADY; WEIL, 2013; RAMOS et al., 2023). In addition, sandy soils with low CEC have low buffering power for K (BRADY; WEIL, 2013). Thus, the low K contents observed in the three areas can be explained by the predominance of the sand fraction and the limitation of CEC.

Ca contents were 1.78, 1.56 and 1.80 cmol$_c$ kg^{-1} for NF, RA and AA, respectively. As pointed out in the literature, for fertility levels, RA exhibited low content, while NF and AA showed medium contents (AQUINO et al., 1993). Regarding Mg, the values were 0.54, 0.68 and 1.58 cmol$_c$ kg^{-1} for NF, RA and AA, respectively, representing low level for NF, medium level for RA and high level for AA (AQUINO et al., 1993). Thus, the higher Mg content contributed to the higher SB value in AA, reflecting better chemical fertility conditions compared to the other areas.

Potential acidity was higher in the NF area, with a value of 1.45 cmol$_c$ kg^{-1}, while RA and AA had values of 0.66 and 0.73 cmol$_c$ kg^{-1}, respectively. In addition to potential acidity, aluminum analysis was performed and the element was not detected in any of the areas. In this context, potential acidity may be associated with the fraction of H^+ in the soil exchange complex (DIAS et al., 2023).

With regard to SB, the values obtained were 2.34, 2.26 and 3.40 cmol$_c$ kg^{-1} for NF, RA and AA, respectively, with all areas classified as medium fertility (PREZOTTI; MARTINS, 2013). SB is sensitive to environmental variations, such as climate and parent material, and is directly related to natural soil fertility (ARAÚJO FILHO et al., 2022).

The highest value observed in AA was mainly influenced by the Ca and Mg contents, since Na and K contents showed little variation among the areas. A similar result was observed by Dias et al. (2023), who identified Ca and Mg as the main cations responsible for SB in less weathered soils, mainly *Cambissolos* (Inceptisols) and *Argissolos* (Ultisols). This result reinforces the SB obtained in the present study, given that all areas are located in *Argissolos* (Ultisols).

Regarding CEC, all areas showed values classified as low, indicating low buffering capacity and lower resistance to pH changes (PREZOTTI; MARTINS, 2013). Selmy et al. (2022) observed that higher levels of organic matter influence higher CEC values. In the present study, although the NF area had the highest TOC content, it was not the one with the highest CEC value.

The low CEC value can be explained by the predominance of the sand fraction in all areas, since CEC depends on the amount and types of colloidal particles, such as humus and clay (SELMY et al., 2022; FARIAS et al., 2023). Sandy soils have low CEC when compared to silt loam and clay loam soils (BRADY; WEIL, 2013).

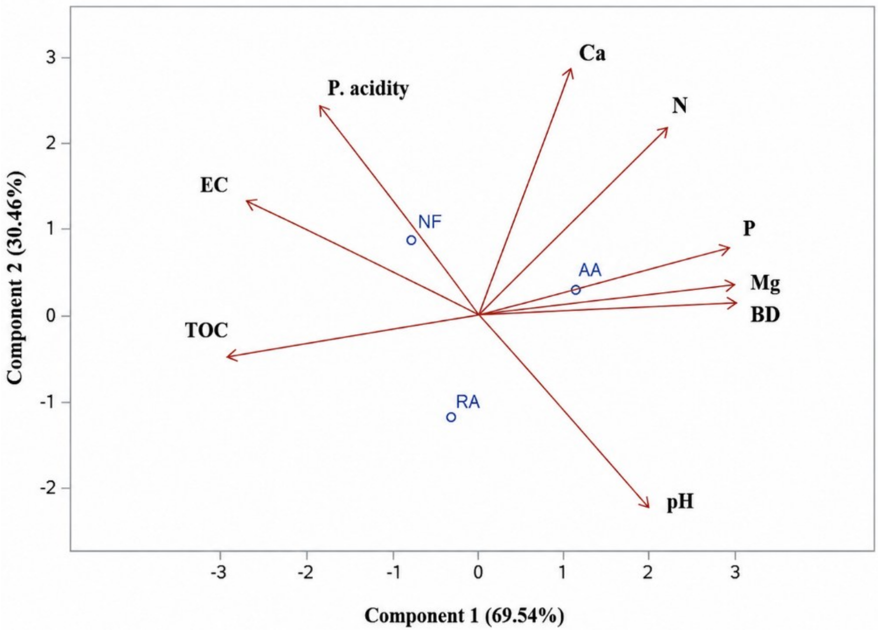
V%, which indicates the percentage of total negative charges occupied by bases, was classified as medium for NF and high for RA and AA (PREZOTTI; MARTINS, 2013). In the Brazilian semi-arid region, most soils are characterized as eutrophic, as characteristics such as high evapotranspiration rates and low rainfall reduce the loss of basic cations (ARAÚJO FILHO et al., 2022).

Succinctly, the results indicate that land use alters the physicochemical attributes of the soil. The NF area stood out with lower BD and higher TOC content, indicating absence of compaction and maintenance of organic matter. This result is a consequence of the management adopted, since it is a preserved area, without anthropic interference.

AA showed an increase in chemical fertility indicators, such as Mg, SB and V%, but had a significant reduction in TOC. Studies carried out in the Brazilian semi-arid region reinforce that agricultural areas tend to have lower TOC contents when compared to preserved areas (MEDEIROS; CESÁRIO; MAIA, 2023; ANDRADE et al., 2020).

In this context, it can be seen that the implementation and adequate management of a CU are associated with the significant TOC content in NF. This behavior can also be observed in RA, in which reforestation, combined with the absence of anthropogenic interventions, resulted in TOC contents close to those of NF. Therefore, in addition to the implementation of a CU, it is essential to adopt management, environmental restoration, monitoring and inspection actions in order to ensure effective conservation and improvement of soil quality over time.

In view of the differences observed in the physicochemical attributes of the soil between the study areas, the PCA was used to synthesize and evaluate the data in an integrated manner. The results of the analyses of BD, TOC, N, pH, EC, P, Ca, Mg and Potential Acidity were used to obtain the correlation matrix between the variables and the principal components (PC) (Figure 4). Although Na and K were analyzed in this study, these variables were not included in the PCA because they exhibited low variability between the areas. Figure 4 shows that PC1 explained 69.54% of the variance, and PC2, 30.46%.



NF: native forest; RA: regenerating area; AA: agricultural area

Figure 4. Biplot graph of the data matrix with the variables and areas according to the principal components.

The PCA characterized the areas according to the physicochemical attributes of the soil (Figure 4). Thus, AA was associated with the attributes BD, N, P, Ca, and Mg, the NF area showed a greater relationship with EC and Potential Acidity, and RA was associated with TOC. Finally, pH is not directly related to any of the areas, suggesting a low contribution of this variable in the characterization of the environments analyzed.

According to the PCA, AA is more related to soil chemical fertility when it comes to the nutrients N, P, Ca and Mg. In the case of BD, this attribute is one of the main factors that differentiate AA from a preserved area, since compaction compromises root growth, reduces aeration and alters water distribution along the soil profile (DIAS et al., 2023). Falcão et al. (2020) identified higher BD values in exposed soil and agricultural areas and lower values in native forest areas, associating the latter result with the absence of grazing and higher TOC content.

In relation to NF, low values of nutrients such as Ca and Mg are consistent with preserved areas, as they are related to the cycling equilibrium capacity, so the nutrients are quickly absorbed by plants, reducing their availability in the soil (COSTA et al., 2018). In addition, higher acidity levels in the soil reduce the availability of exchangeable bases (RAMOS et al., 2023; COSTA et al., 2018). Although NF had a higher EC value, the observed values are very low, indicating no risk of salinity (FARIAS et al., 2023).

In turn, RA was characterized by the association with TOC. This variable reinforces the reestablishment of vegetation, favoring the input of litter and contributing to the incorporation of carbon into the soil (SILVA et al., 2024). In contrast, the conversion of vegetated areas to conventional systems can result in losses of soil organic carbon (MEDEIROS; CESÁRIO; MAIA, 2023).

Based on this characterization of the areas, it is important to evaluate the values of the principal components, as shown in Table 3.

Based on the eigenvectors presented in Table 3, it can be observed that PC1 was mainly influenced by the variables BD, TOC, EC, P and Mg, representing a gradient associated with soil structure and fertility. PC2 represents a gradient related to N, pH, potential acidity, and Ca.

As described in the methodology, MANOVA was carried out to identify differences between the areas through the chemical attributes of the soil (TOC, N, pH, EC, P, Potential Acidity, Ca and Mg). Thus, the results obtained are presented in Table 4.

Table 3. Eigenvectors of the principal components.

	PC1	PC2
BD	0.397912	0.040180
C	-.392576	-.106751
N	0.283519	0.427037
pH	0.280441	-.431725
EC	-.366173	0.240514
P	0.392761	0.105158
Potential Acidity	-.256849	0.464518
Ca	0.133900	0.571991
Mg	0.395317	0.079919

Table 4. MANOVA and F approximations for all areas.

Statistics	Value	F Value	DF Num	DF Den	Pr > F
Wilks' Lambda	0.02210283	3.58	16	10	0.0231
Roy's largest root	1.62372513	3.24	16	12	0.0226
Pillai's trace	15.02383112	4.47	16	5.4118	0.0456
Lawley-Hottelling's trace	12.72820032	9.55	8	6	0.0065

DF Num: degrees of freedom of the numerator; DF Den: degrees of freedom of the denominator; Pr > F: probability greater than F of the p-value.

All the p-values obtained are lower than 0.05, allowing the rejection of H_o and indicating that there is at least a significant difference between the mean vectors of the areas considering the four statistics. Based on this result, specific contrasts between the areas (AA vs. RA, AA vs. NF, and RA vs. NF) were tested, and the results are presented in Tables 5, 6, and 7.

Table 5. MANOVA and F approximations for the AA vs RA contrast.

Statistics	Value	F value	DF Num	DF Den	Pr > F
Wilks' Lambda	0.09182751	6.18	8	5	0.0301
Roy's largest root	0.90817249	6.18	8	5	0.0301
Pillai's trace	9.88998241	6.18	8	5	0.0301
Lawley-Hottelling's trace	9.88998241	6.18	8	5	0.0301

DF Num: degrees of freedom of the numerator; DF Den: degrees of freedom of the denominator; Pr > F: probability greater than F of the p-value.

Table 6. MANOVA and F approximations for the AA vs NF contrast.

Statistics	Value	F value	DF Num	DF Den	Pr > F
Wilks' Lambda	0.08815578	6.46	8	5	0.0274
Roy's largest root	0.91184422	6.46	8	5	0.0274
Pillai's trace	10.34355603	6.46	8	5	0.0274
Lawley-Hottelling's trace	10.34355603	6.46	8	5	0.0274

DF Num: degrees of freedom of the numerator; DF Den: degrees of freedom of the denominator; Pr > F: probability greater than F of the p-value.

Table 7. MANOVA and F approximations for the RA vs NF contrast.

Statistics	Value	F value	DF Num	DF Den	Pr > F
Wilks' Lambda	0.30282766	1.44	8	5	0.3580
Roy's largest root	0.69717234	1.44	8	5	0.3580
Pillai's trace	2.30220824	1.44	8	5	0.3580
Lawley-Hottelling's trace	2.30220824	1.44	8	5	0.3580

DF Num: degrees of freedom of the numerator; DF Den: degrees of freedom of the denominator; Pr > F: probability greater than F of the p-value.

For AA vs RA and AA vs NF, the p-values were lower than 0.05 (0.03 and 0.02, respectively), indicating a significant difference between the mean vectors. However, the contrast RA vs NF was not significant (0.36), indicating that RA has a chemical behavior similar to that of NF. This result suggests that the regeneration process has been gradually reestablishing the ecological functions of the soil, since the increase in vegetation cover favors litter deposition, incorporation of carbon into the soil, and intensification of nutrient cycling (SILVA et al., 2024). This analysis reinforces the role of regeneration in bringing the chemical attributes of the two areas closer together.

CDA was used to evaluate the discrimination between the three areas, AA, RA, and NF, based on the chemical attributes (TOC, N, pH, EC, P, Ca, Mg, and Potential Acidity), as presented in Figure 5. In addition, it is also important to evaluate the points within each area, as dispersion demonstrates internal variability. While NF showed lower dispersion, suggesting greater homogeneity of chemical attributes and, possibly, more stable ecological conditions, RA and AA exhibited greater variability.

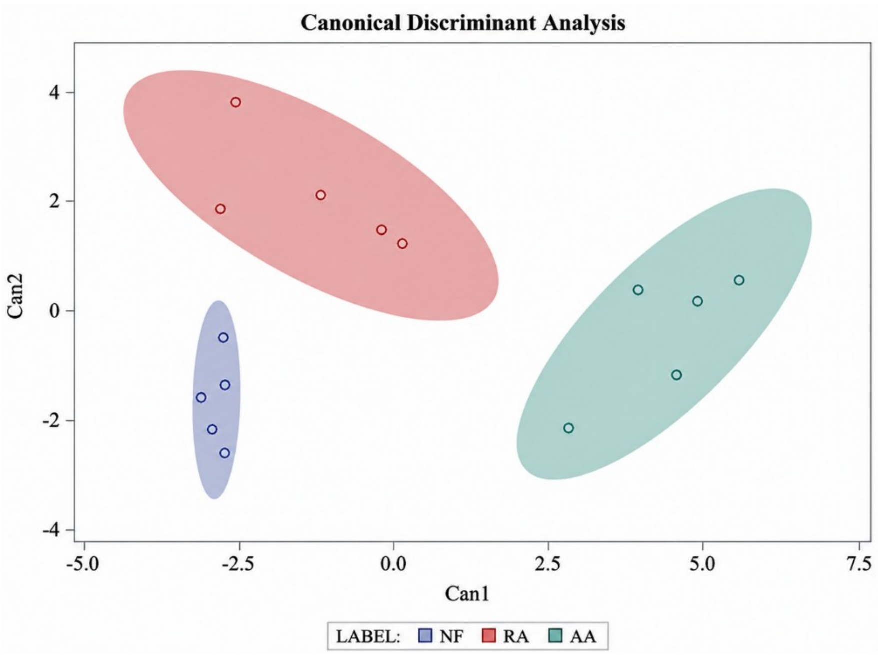


Figure 5. Discriminant plot for separation of the study areas with confidence ellipses (95%) for the mean vectors.

As presented in Figure 5, the CDA showed visible discrimination between the groups, with no overlap of the confidence ellipses (95%). CAN1 was responsible for distinguishing AA from the areas with less anthropogenic interference (NF and RA). In turn, CAN2 promoted the separation between NF and RA, indicating differences in soil attributes associated with the different stages of conservation and regeneration. The canonical coefficients of the discriminant variables are presented in Table 8.

Table 8. Canonical Coefficients for the discriminant analysis.

	Canonical coefficients	
Variables	CAN 1	CAN 2
TOC	-0.867623677	1.600937818
N	3.527016332	-6.968887104
pH	4.413146391	5.747222645
EC	-0.003262647	0.022474464
P	0.082410954	0.218275579
Potential Acidity	1.196108274	-0.048821231
Ca	-0.273773242	-2.665535071
Mg	4.216300734	1.637763225

To identify the variables that had the most weight in the discrimination of treatments, a cut was made for those with values above 2. Thus, for CAN1, the variables pH, Mg and N showed the highest canonical coefficients, indicating that this axis is mainly associated with soil chemical fertility, being responsible for the distinction of AA from the other areas. On the other hand, CAN2 was mainly influenced by N (negatively), pH (positively) and Ca (negatively), suggesting a gradient related to acidity conditions and nutrient dynamics, contributing to the separation between the NF and RA areas.

In addition to the CDA, Tukey test (Figure 6) was applied to compare the means of the groups.

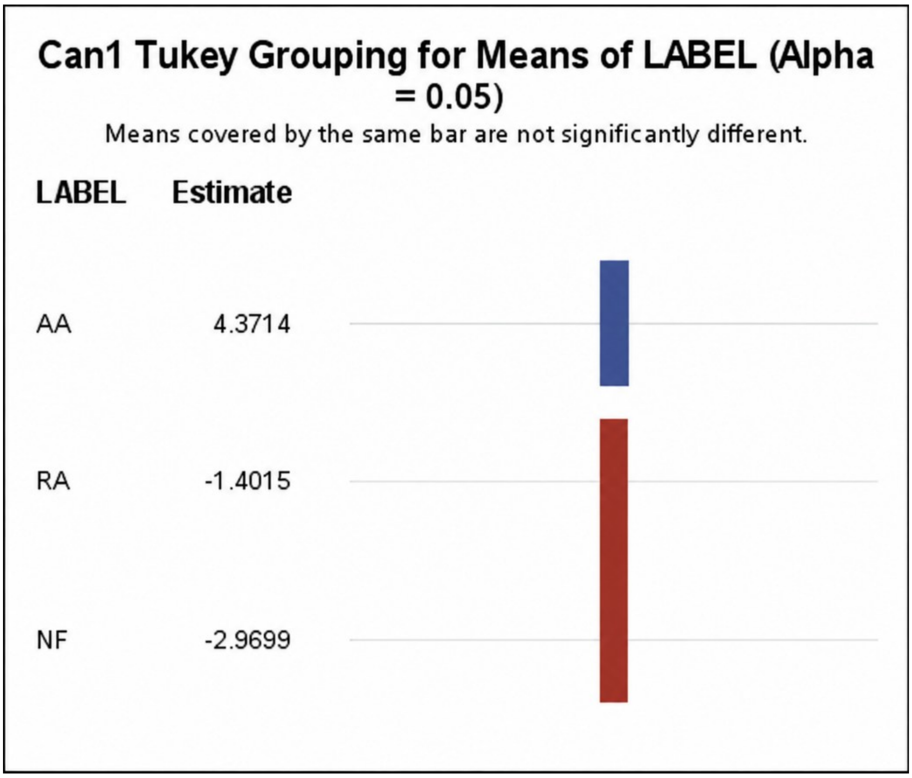


Figure 6. Tukey test performed for the areas.

The comparison of the means of CAN1 scores by Tukey test statistically confirmed the separation observed in the CDA, indicating that AA differs significantly from the other areas, while RA and NF did not differ significantly from each other. This result reinforces that CAN1 is associated with the effect of agricultural use on soil attributes.

CONCLUSION

The results showed that agricultural use promotes significant changes in the physicochemical attributes of the soil, particularly increment in bulk density and reduction in organic carbon, indicating structural degradation and loss of quality. In contrast, the native forest showed better edaphic conditions, associated with the maintenance of natural processes, while the regenerating area showed similar characteristics, highlighting the effectiveness of fallow and reforestation for soil restoration. Multivariate analyses confirmed the distinction of the agricultural area from the others, as well as the proximity between native forest and regenerating area, reinforcing the role of conservation strategies. In this context, the PNHR proved to be a relevant instrument for soil conservation and restoration of degraded areas in the semi-arid region.

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REFERENCES

AMARAL FILHO, J.; ASSIS JÚNIOR, R. N.; MOTA, J. C. A. **Física do Solo: Conceitos e Aplicações**. Fortaleza, CE: Imprensa universitária, 2008. 290 p.

ANDRADE, E. M. et al. Land-Use Effect on Soil Carbon and Nitrogen Stock in a Seasonally Dry Tropical Forest. **Agronomy**, 10: 1-14, 2020.

AQUINO, A. B. et al. **Recomendações de Adubação e Calagem para o Estado do Ceará**. Fortaleza, CE: UFC, 1993. 247 p.

ARAÚJO FILHO, J. C. et al. Solos do Semiárido: características e estoque de carbono. IN: GIONGO, V.; ANGELOTTI, F. (Eds.). **Agricultura de baixa emissão de carbono em regiões semiáridas: experiência brasileira**. Brasília, DF: EMBRAPA, 2022. cap. 6, p. 93-112.

BRADY, N. C.; WEIL, R. R. **Elementos da natureza e propriedades dos solos**. 3. ed. Porto Alegre, RS: Bookman, 2013. 686 p.

BRASIL. **Lei nº 9.985, de 18 de julho de 2000**. 2000. Available at: <https://www.planalto.gov.br/ccivil_03/leis/l9985.htm>. Access on: Jan. 28, 2026.

CLAESSAN, M. E. C. **Manual de Métodos de Análise de Solo**. 2 ed. Rio de Janeiro, RJ: Embrapa Solos, 1997. 212 p.

COSTA, T. G. A. et al. Atributos de qualidade do solo sob fitofisionomias de cerrado sensu stricto e cerradão no Parque Nacional das Nascentes do Rio Parnaíba. **Revista Brasileira de Gestão Ambiental e Sustentabilidade**, 5: 625-642, 2018.

DIAS, P. M. S. et al. Soil Attributes and Their Interrelationships with Resistance to Root Penetration and Water Infiltration in Areas with Different Land Uses in the Apodi Plateau, Semiarid Region of Brazil. **Agriculture**, 13: 2-24, 2023.

FALCÃO, K. S. et al. Estoques de carbono e agregação do solo sob diferentes sistemas de uso no cerrado. **Revista Brasileira de Ciências Ambientais**, 55: 242-255, 2020.

FARIAS, P. K. P. et al. Characterization and Classification of Soils in Agroecosystems in a Moist Enclave in Northeastern Brazil. **Land**, 12: 1-15, 2023.

FUNCEME - Fundação Cearense de Meteorologia e Recursos Hídricos. **Levantamento de reconhecimento de média intensidade dos solos do Estado do Ceará**. 1. ed. Fortaleza, CE: Funceme, 2024. 181 p.

GAVA, C. A. T. et al. Land- use change alters the stocks of carbon, nitrogen, andphosphorus in a Haplic Cambisol in the Brazilian semi-aridregion. **Soil Use Manage**, 38: 953-963, 2022.

IPECE - Instituto de Pesquisa e Estratégia Econômica do Ceará. **Perfil municipal 2017 Quixadá**. 2017. Available at: <https://www.ipece.ce.gov.br/wp-content/uploads/sites/45/2018/09/Quixada_2017.pdf>. Access on: Jan. 28, 2026.

INSA - Instituto Nacional do Semiárido. **O Semiárido Brasileiro**. Available at: < https://www.gov.br/insa/pt-br/semiaridobrasileiro#:~:text=Segundo%20dados%20do%20INSA%2C%2085,protege%20o%20solo%2>. Access on: Jan. 28, 2026.

KARAVIDAS, I. et al. Hydroponic Common-Bean Performance under Reduced N-Supply Level and Rhizobia Application. **Plants**, 12: 1-17, 2023.

MEDEIROS, A. S.; CESÁRIO, F. V.; MAIA, S. M. F.; Long-term impact of conventional management on soil carbon and nitrogen stocks in the semi-arid region of Brazil: A meta-analysis. **Journal of Arid Environments**, 218: 1-10, 2023.

MENDES, F. E. et al. Recursos hídricos e solos. In: YONG, C. E. F.; MEDEIROS, R. (Eds.). **Quanto vale o verde: a importância econômica das unidades de conservação brasileiras**. Rio de Janeiro, RJ: Conservação Internacional, 2018. cap. 6, p. 119-149.

MENDONÇA, E. S.; MATOS, E. S. **Matéria orgânica do solo: métodos de análises**. Viçosa, MG: UFV, 2005. 107 p.

NASCIBEM, F. G. et al. The Role of Private Reserves of Natural Heritage (RPPN) on natural vegetation dynamics in

Brazilian biomes. **Land Use Policy**, 132: 1-11, 2023.

PAIVA, C. D. G et al. Fitossociologia da caatinga na Floresta Nacional de Açu, Estado do Rio Grande do Norte, Brasil, e entorno: diversidade e biogeografia do componente lenhoso. **Hoehnea**, 48: 1-11, 2021.

PREZOTTI, L. C.; MARTINS, A. G. **Guia de interpretação de análise de solo e foliar**. 1. ed. Vitória, ES: Incaper, 2013. 104 p.

RAMOS, R. S. et al. Avaliação dos atributos do solo submetidos a diferentes usos e manejos do solo no semiárido paraibano. **Recima 21**, 4: 1-15, 2023.

REINPRECHT, Y. et al. Effects of Nitrogen Application on Nitrogen Fixation in Common Bean Production. **Frontiers in Plant Science**, 11: 1-19, 2020.

SILVA, J. M. C.; PINTO, P. L.; SCARANO, F. R. Toward integrating private conservation lands into national protected area systems: Lessons from a megadiversity country. **Conservation Science and Practice**, 3: 1-8, 2021.

SILVA, L. F. S. et al. Changes in Soil C, N, and P Concentrations and Stocks after Caatinga Natural Regeneration of Degraded Pasture Areas in the Brazilian Semiarid Region. **Sustainability**, 16: 1-13, 2024.

SELMY, S. A. H. et al. Impact of Short-Term Cultivation on Some Selected Properties of Sandy Soil in an Arid Environment. **Soil Systems**, 6: 1-22, 2022.

SOUZA, D. G. et al. Multiple drivers of aboveground biomass in a human-modified landscape of the Caatinga dry forest. **Forest Ecology and Management**, 435: 57-65, 2019.

TEIXEIRA, P. C. et al. **Manual de métodos de análise de solo**. 3. ed. Brasília, DF: Embrapa, 2017. 574 p.

VASCONCELOS, W. A. S. **Atributos do solo sob diferentes sistemas de manejo na região Jaguaribana do Ceará**. 2022. 66 f. Dissertação (Mestrado em Ciência do Solo: Área de Concentração em Manejo do Solo e da Água) – Universidade Federal do Ceará, Fortaleza, 2022.