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Physical, Chemical, and Microbiological Properties of Soil under Different Plant Covers in the Seridó Desertification Region in the Brazilian Semiarid

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ABSTRACT: The Seridó Desertification Region is a result of inadequate management of the native Caatinga vegetation, which generated degraded areas with little or no capacity for plant production. The area has experienced a succession of different land uses, but little is known about the impact of these changes. The present study tested the hypothesis that the intense degradation of the Caatinga drastically decreased vegetal biomass production, which favored direct soil exposure and resulted in a lower abundance and diversity of species and groups of vegetation as well as microorganisms. This study aimed to quantify some of the main physical, chemical, and microbiological properties of Alfisol (*Luvissolo Crômico órtico lítico*) and Entisol (*Neossolo Litólico eutrófico típico*) under different plant covers in the Seridó Desertification Region, in the municipality of Parelhas, in the state of Rio Grande do Norte (RN), Brazil. Three different areas were studied: an area of preserved Caatinga, a recovery area with jurema [*Mimosa tenuiflora* (Willd.) Poir.], and a degraded area. Soil samples were collected from the 0.00-0.10 m soil layer and later characterized in terms of their physical and chemical properties. The microbiological characteristics analyzed were microbial activity (microbial biomass carbon and microbial respiration) and glomalin. The soil under the Caatinga vegetation exhibited better properties than the other analyzed soils. Aggregate stability was the physical property with the highest potential for differentiating between areas. Glomalin, which is associated with the presence of mycorrhizae, and which, in turn, is related to the uptake of P, which is often deficient in these soils, was the most discriminating microbiological variable according to an analysis of canonical variables. The total of Ca^{2+} and Mg^{2+} was the most discriminating chemical properties, and played a positive role in soil aggregation, especially Ca^{2+}.

Keywords: soil fertility, soil structure, soil microbial activity.

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INTRODUCTION

The development model in the Brazilian semiarid region has been based on predatory logging for wood, fuel, and intensive agriculture with deforestation and burning followed by extensive overgrazing by livestock, resulting in changes in the plant cover. The main consequences of this model are decreases in the natural renewable resources of the Caatinga and soil degradation (Araújo Filho and Barbosa, 2000).

Crop production depends on nutrient availability during the crop cycle, especially of N and P, which are released along organic matter mineralization. When the nutrient release rates are lower than the crop demands, crop productivity drastically decreases (Salcedo et al., 1997). This effect resulted in a 30 % loss of C and N after six years of cultivation in Chapada de Araripe in semiarid northeastern region of Brazil (Tiessen et al., 1992). The authors reported that 30 % of the organic P was converted into inorganic P forms during the same period. Worldwide, 2 billion hectares are estimated to have been degraded due to inadequate soil use and management, climate factors, and extractive agriculture (Lal, 1997).

Therefore, there is growing interest in studying parameters that indicate soil changes early and effectively; and in investigating adequate methods to preserve or improve the soil quality and guarantee the sustainability of ecosystems (Chaer et al., 2009; Mendes et al., 2009). Soil changes in response to a given condition and/or management system can only be understood through the integrated analysis of a minimum set of parameters thought to be affected by different soil uses that influence the ecological system as a whole (Alvarenga and Davide, 1999; Casalinho et al., 2007).

To achieve sustainability, it is important to establish evaluation criteria and monitoring methods to evaluate the effects of human activities and reorient them (Leonardo, 2003). Indicator parameters for the soil conservation and/or degradation status need to be identified to evaluate the soil quality (Zilli et al., 2003).

The evaluation and effective identification of these parameters are complicated due to the multiplicity of factors involved. Multivariate statistics are increasingly used for the analysis of complex data sets (Tabachnick and Fidell, 2007). This approach allows the analysis of large numbers of variables and can be used to develop soil quality indices by distinguishing areas based on the soil status and/or management system and determining the most important parameters/properties for their characterization (Sena et al., 2002). Although multivariate statistical analysis increases the capacity for data extraction and interpretation compared with univariate and bivariate methods, this approach has been used in few soil studies. Semiarid regions, where changes in soil use have been especially intense, present a unique opportunity to study the interrelationships between properties in soil and plant cover, using multivariate methods.

The present study tests the hypothesis that the intense Caatinga degradation drastically decreases vegetal biomass production, thereby increasing direct soil exposure. This exposure results in a lower abundance and diversity of species and groups, as much for the vegetation as for microorganisms, and in changes in soil fertility, thereby increasing soil erosion.

The aim of the present study was to quantify some of the main physical, chemical, and biological properties of two different soils from the Seridó Desertification Region located in the municipality of Parelhas, in the state of Rio Grande do Norte (RN), Brazil, collected from different areas and strata during the dry season. Our results contribute to the understanding of the desertification phenomenon in the Brazilian semiarid regions.

MATERIALS AND METHODS

The study was performed at Esperança Farm, in the municipality of Parelhas (6° 41' 16" S, 36° 39' 28" W), in the state of Rio Grande do Norte, Brazil, approximately 245 km from the state capital of Natal (RN). This region is considered one of the areas most affected by desertification in the state.

The region's climate is BSh according to the Köppen climate classification system, which is characterized as usually hot and dry or semiarid, with short periods of irregular rainfall during the summer and autumn, and a prolonged dry season. The area has an average annual temperature between 25-27 °C and an average annual rainfall between 380-450 mm (Beltrão et al., 2005). The area is characterized by Precambrian formations with the occurrence of Cambrianto Quaternary stratigraphic sequences (Angelim, 2006).

Soil sampling

Two types of soils were evaluated: an Alfisol (*Luvissolo Crômico órtico lítico*) and Entisol (*Neossolo Litólico eutrófico típico)* collected during the dry season (November 2012). Alfisols present in hills forming open V-shaped valleys that have slopes that are tens of meters highland is associated with plateaus exhibiting valleys and inselbergs (Vieira, 1983) and chromic soils in most of the B horizon, classified according to Santos et al. (2013). Entisols poorly developed, is shallow or very shallow (approximately 0.40 m depth), and sits directly on rock or crystalline basement rocks, leading to the constant appearance of stones and rocks at the soil surface and frequent rocky outcrops (Vieira, 1983). Soils with the A or histic horizon sit directly on rock and/or Cr horizon or on material constituted by 90 % or more (per unit volume) rock fragments with diameters larger than 2 mm and lithic or fragmentary contact within a 0.50 m depth (Santos et al., 2013).

Three study areas were selected for each soil as follows: a) preserved Caatinga (C), an area without human interference for the last twenty years; b) recovery area with jurema (R): an area previously explored for cotton production that has not been cultivated for the last ten years; and c) degraded area (D): an area used for the production of several grasses and legumes for many years. But that has lacked plant cover for the last eight years. Main species in the preserved Caatinga include: *Poincianella pyramidalis* (Tul.) L. P. Queiroz, commonly known in Brazil as "catingueira"; *Croton sonderianus* (Muell.) Arg., commonly known in Brazil as "marmeleiro"; and *Mimosa tenuiflora* (Willd.) Poir, commonly known in Brazil as "jurema-preta".

The different soil-plant cover combinations were called strata (seven in total), and are as described below and shown in table 1. An area of one hectare was delimited in each stratum by taking into consideration the relief variations and opting for a homogeneous area with relatively flat relief. Three 3 × 3 m sampling plots 10 m apart were randomly chosen in each stratum.

In the preserved Caatinga (C) area, the sampling plots were positioned so that they included soil from under three tree species [catingueira (Cat), jurema (Jur), and marmeleiro (Mar)] and an area without vegetation called "between trees" (bt). These plots were considered to represent four different strata. For each stratum, three soil samples were collected, combined, and homogenized into a composite sample. The soil samples associated with the tree species were collected in their crown projection area.

At the covery area with jurema (R), the sampling plots were positioned so that they included jurema plants (Jur) with the same size, considering the same size as before, and an area without vegetation (between trees, bt) in two different strata. Composite soil samples were obtained for each stratum.

Table 1. Identification of the studied soils, areas, and strata

Soil	Area	Stratum	Abbreviation
Alfisol	Preserved Caatinga	Catingueira	LCCat
		Jurema	LCJur
		Marmeleiro	LCMar
		Between trees	LCbt
	Recovery area	Jurema	LRJur
		Between trees	LRbt
	Degraded area	No vegetation	LD
Entisol	Preserved Caatinga	Catingueira	NCCat
		Jurema	NCJur
		Marmeleiro	NCMar
		Between trees	NCbt
	Recovery area	Jurema	NRJur
		Between trees	NRbt
	Degraded area	No vegetation	ND

At the degraded soil area (D), three points were randomly selected in each sampling plot for soil collection. At each point, considered a replicate, three simple subsamples were collected, which were homogenized, thereby obtaining a composite sample.

For each sampling point described above, a block of soil measuring 0.15 x 0.15 x 0.10 m (width × length × depth) was collected (adapted from Anderson and Ingram, 1993). This sampling method was selected because collection using an auger was not possible due to the stony and/or rocky soil types.

The collected samples were stored in plastic bags, placed in Styrofoam boxes, and sent to the laboratory for analysis. The samples were processed for biological properties, the microbial biomass, microbial respiration, and glomalin measurements. Additionally, the physical and chemical properties of the studied soils were evaluated.

Soil physical characterization

Clay dispersion in water was measured by particle size analysis according to the Bouyoucos hydrometer method (Teixeira et al., 2017) without a chemical dispersant. Total clay was measured using the same procedure with sodium hydroxide (NaOH 1 mol L^{-1}) as the dispersant. The degree of flocculation was calculated using the equation 1:

$$DF = \left(\frac{Clay - Clay_{H_2O}}{Clay} \right) \times 100 \quad \text{Eq. 1}$$

in which *Df* is the degree of flocculation (%), Clay is the clay dispersion in NaOH (g kg^{-1}), and $Clay_{H_2O}$ is the clay dispersion in water (g kg^{-1}).

The bulk density and particle density were determined according to Teixeira et al. (2017). The total porosity was estimated using the equation 2:

$$Pt = 1 - \frac{Bd}{Pd} \quad \text{Eq. 2}$$

in which *Pt* is the total porosity (m^3 m^{-3}), Bd is the bulk density (Mg m^{-3}) and Pd is the particle density (kg m^{-3}).

To determine the mean weight diameter of soil aggregates (MWD), samples were processed according to Arshad et al. (1996), except that a 4 mm instead of an 8 mm

mesh sieve was used to establish the upper limit of the aggregate diameter class. Soil aggregates (1-2 mm) were separated by dry sieving and used to determine the percentage of water stable aggregates (WSA) (Nimmo and Perkins, 2002). All samples were analyzed in triplicate.

Soil chemical characterization and fertility

Analyses of chemical properties and soil fertility, performed in triplicate, determined the pH(H_2O), exchangeable and organic matter, total bases, cation exchange capacity, saturation percentage, and available P, K^+, Na^+, Ca^{2+}, Mg^{2+}, and Al^{3+}, according to Teixeira et al. (2017). Sulfur content was also analyzed according to Tedesco et al. (1995).

Evaluation of microbial activity

Microbial biomass carbon (MBC) was determined by the fumigation-extraction method, according to Vance et al. (1987).

The MBC was calculated using the equation 3:

$$MBC = \frac{FC - NFC}{KEC} \quad \text{Eq. 3}$$

in which FC and NFC are the carbon extracted from the fumigated and non-fumigated soils, respectively, and *KEC* is the percent microbial carbon extracted following fumigation, which is 0.33 % for tropical soils (Feigl et al., 1995).

To determine microbial respiration, the samples were processed according to Vance et al. (1987). First, 32 g of soil from each sample was weighed and placed in a 50 mL transparent glass jar with an airtight lid. A control without soil was included. Then, a container with 4 mL of NaOH 0.5 mol L^{-1} (sodium hydroxide) was placed in each jar for CO_2 capture. The jars were hermetically sealed and left at room temperature (approximately 28 °C) in the dark. After seven days, the NaOH 0.5 mol L^{-1} solutions were removed from the jars, and 3 mL of $BaCl_2$ 20 % was added. Immediately before titration, the NaOH 0.5 mol L^{-1} solutions were transferred to labelled Erlenmeyer flasks, and a drop of phenolphthalein was added. The titration was performed with HCl 0.1 mol L^{-1} previously standardized with phthalic acid (modified from Vance et al., 1987).

Glomalin was extracted according to Wright and Upadhyaya (1996). One gram of soil was added to 8 mL of sodium citrate buffer and autoclaved at 121 °C for 30 min. One milliliter of Bradford reagent was added, and the quantity of bovine serum albumin (BSA) (mg mL^{-1}) released during autoclaving was determined by spectrophotometry (λ = 595 nm). For the evaluation of the microbial activity, all of the samples were analyzed in triplicate.

Data analysis and systematization

In order to evaluate the results of the different vegetation cover, uses, and soil types in soil quality (QS) with physical, chemical, and microbiological properties, the data were evaluated through analysis of variance (ANOVA). Comparisons of averages were performed using the Tukey test at 5 % probability, with the aid of SAS software (SAS, 1989).

Subsequently, the CANDISC procedure was used for the analysis of canonical variables. A data matrix was constructed for the physical, chemical, and microbiological properties data (SQ matrix), and the data were relativized by columns using the PC-ORD v 4.0 program (McCune and Mefford, 1999). Standardized canonical coefficients, mean canonical variate scores, and group dispersions and formations based on canonical variate scores were analyzed using the CANDISC procedure in SAS (SAS Institute, 1989).

RESULTS AND DISCUSSION

According to canonical analysis, differences in soil exchangeable cations (especially Ca^{2+} and Mg^{2+}) were observed between the different soils, areas, and strata studied. Exchangeable cations play important roles in the exchange complex and soil solution and in clay flocculation and dispersion. Their increases, although not statistically significant, can be explained by the gradual exposure of the soil parent material caused by erosion. As the sediments in the superficial layers are transported by erosion, soil horizons closer to the parent rock are exposed. These matrices have not suffered weathering and retain the nutrients from the time of their formation (Table 2). In the case of the Seridó range, consist of a lower meta-volcano-sedimentary sequence called the Serra dos Quintos formation and a siliciclastic and carbonate rock shelf (Angelim, 2006).

Therefore, the lower clay dispersion associated with a higher degree of flocculation (Table 3) observed in the studied soils, areas, and strata might be related to the Ca^{2+} and Mg^{2+} contents relative to the soil CEC (Table 3). Indeed, the total organic carbon, which was classified as low, varied from 4.57-7.33 g kg^{-1}, and the soil texture was predominantly sandy loam. A higher degree of clay flocculation indicates a lower tendency for microaggregate disaggregation (base of the soil aggregate hierarchy). Microaggregates are essentially formed by flocculated clay stabilized by cement agents, such as organic matter and Fe and Al oxides (Reichert and Norton, 1995; Hillel, 2003). In this case, according to the analysis of variance and the canonical coefficients obtained in the present study, the lower dispersed clay and consequently higher flocculation degree contributed to explain much of the observed aggregate stability.

As for physical properties, there was an increase in soil density in both soils, especially in areas with anthropogenic action, which corresponded to the area under recovery with jurema, being 1.48 and 1.47 g cm^{-3} for *Luvissolo* and *Neossolo*, respectively, but it did not differ significantly from the degraded area. Meanwhile, the spaces between trees of the preserved Caatinga present a lower soil density in both soils (Table 3). This tendency also continues to be observed in the total porosity of the soil, which was between 0.44 and 0.45 m^3 m^{-3} (although it is not so clearly due to variations in particle density i.e.

Table 2. Mean values of chemical properties of the Alfisol and Entisol from the Preserved Caatinga (strata: catingueira, jurema, marmeleiro, and between trees), Recovery Area with jurema (strata: jurema and between trees), and Degraded Area without plant cover, at a layer of 0.00-0.10 m, in the dry period

Soil	Area	pH(H_2O)	P	K	Na	H+Al	Ca^{2+}	Mg^{2+}	SO_4	COT	SB	CTC	V
			———	mg kg^{-1}	———	———	$cmol_c$ kg^{-1}	———	mg L^{-1}	g kg^{-1}	——	$cmol_c$ kg^{-1}	——	%
Alfisol	Preserved Caatinga	5.6 Aa	6.38 Aa	365 Ba	69 Ab	3.01 Aa	3.46 Aa	2.95 Aa	4.15 Bb	7.30 Aa	6.85 Aa	9.9 Aa	69.1 Aa
	Recovery area	5.6 Aa	3.42 Aa	384 Aa	103 Ab	2.39 Bab	2.95 Aa	3.03 Aa	3.08 Bb	5.00 Aa	6.75 Aa	9.1 Aa	72.7 Aa
	Degraded area	5.8 Aa	3.54 Aa	481 Aa	266 Aa	1.98 Ab	3.40 Aa	4.06 Aa	10.75 Aa	4.96 Aa	8.21 Aa	10.2 Aa	79.9 Aa
Entisol	Preserved Caatinga	5.6 Aa	3.97 Aa	525 Aa	80 Aa	2.95 Aa	2.86 Aa	2.55 Aa	8.69 Aa	7.33 Aa	6.02 Aa	9.0 Aa	64.8 Aa
	Recovery area	5.6 Aa	3.60 Aa	475 Aa	63 Aa	3.01 Aa	2.48 Aa	2.24 Aa	10.63 Aa	5.30 Aa	5.26 Aa	8.3 Aa	63.4 Ba
	Degraded area	5.4 Ba	6.71 Aa	438 Aa	56 Ba	2.20 Aa	2.05 Aa	1.95 Aa	12.17 Aa	4.57 Aa	4.49 Ba	6.7 Aa	66.6 Ba
CV (%)		4.67	62.31	28.26	57.71	18.95	38.36	49.30	32.26	38.58	34.49	24.37	10.76

pH in water at 1:2.5 ratio; P, K, and Na were extracted with Mehlich-1; H+Al extracted with calcium acetate at pH 7.0 titrated with 0.025 mol L^{-1} sodium hydroxide and 10 g L^{-1} phenolphthalein as indicator was used as the extraction solution; Ca^{2+} and Mg^{2+} were extracted with KCl 1 mol L^{-1}; COT = total organic carbon, obtained by oxidation of the organic matter via wet with 0.116 mol L^{-1} of potassium dichromate in sulfuric medium titrated with 0.4 mol L^{-1} ammoniacal ferrous sulfate with 10 g L^{-1} of diphenylamine as indicator of color change (Yeomans and Bremner, 1988); SB = sum of bases; CTC = effective cation exchange capacity; V = bases saturation; CV = coefficient of variation. Means followed by the same capital letter within in the column between soils for each area, and the same lower case letter between areas for each soil, did not differ statistically by the Tukey test, at the 5 % probability level.

Table 3. Analysis of total and dispersed clay in water, flocculation degree, soil and particle density, total porosity, and soil aggregation of the superficial layers of a Alfisol and a Entisol evaluated from the preserved Caatinga (strata: catingueira, jurema, marmeleiro, and between trees), the recovery area with jurema (strata: jurema, and between trees), and the degraded area without plant cover, at the layer of 0.00-0.10 m, in the dry period

Soil	Area	Sand	Silt	Clay		Degree of flocculation	Density		Total Porosity	Aggregation	
				Total	Dispersed in water		Soil	Particle		DMA	ESTAGREG
		g kg^{-1}				%	kg m^{-3}		m^3 m^{-3}	mm	%
Alfisol	Preserved Caatinga	755 Aa	130 Aa	115 Aa	16 Aa	85.7 Ab	1.35 Ab	2.64 Aa	0.49 Aa	0.61 Aa	39 Aa
	Recovery area	793 Ba	123 Aa	84 Bb	11 Bab	87.3 Aab	1.48 Aa	2.60 Aa	0.44 Ab	0.72 Aa	28 Aa
	Degraded area	770 Aa	122 Aa	108 Aab	0 Bb	100 Aa	1.43 Aab	2.59 Aa	0.45 Ab	0.65 Aa	27 Aa
Entisol	Preserved Caatinga	755 Ab	130 Aa	115 Aa	22 Aa	80.5 Aa	1.35 Ab	2.66 Aa	0.49 Aa	0.53 Aa	31 Ba
	Recovery area	803 Aa	87 Bb	110 Aa	30 Aa	73.2 Bab	1.47 Aa	2.66 Aa	0.45 Ab	0.46 Ba	28 Aa
	Degraded area	787 Aab	118 Aab	95 Aa	34 Aa	63.8 Bb	1.42 Aab	2.66 Aa	0.47 Aab	0.36 Ba	28 Aa
CV (%)		13.05	22.08	17.66	45.71	10.91	4.12	2.19	5.03	24.21	28.21

The clay dispersed in water was obtained by means of soil particle size analysis, according to the Bouyoucos method (Teixeira et al., 2017), but without the use of the chemical dispersant; total clay used the same procedure as above, however, using sodium hydroxide (NaOH 1 mol L^{-1}) as the dispersing agent; soil density and particle density were determined according to the methodologies described in Teixeira et al. (2017); DMA = average diameter of aggregates (Arshad et al., 1996); ESTAGREG = stability of aggregates; CV = coefficient of variation. Within each column, means followed by the same capital letter, between soils for each area, and followed by a lower case letter between areas for each soil, did not differ statistically by the Tukey test, at the 5 % probability level.

2.60 and 2.66 g cm^{-3}, respectively). In the mean diameter of aggregates (DMA), which varied between 0.46-0.72 mm in the stability of aggregates, in both soils, 27 and 39 %.

The Alfisol exhibited very low clay water dispersion only for the stratum between trees and the degraded area. In some cases, this phenomenon coincided with a higher MWD and a high Ca^{2+} and Mg^{2+} content, which might have contributed to higher clay flocculation and improved soil structuring (Tables 2 and 3).

The highest glomalin contents (5.2-5.8 g of soil) and rates of microbial respiration (190-212 mg kg^{-1} C-CO_2) were also observed for the tree strata in the preserved Caatinga areas for both soils. However, for the Entisol, microbial respiration was higher for the tree strata in the recovery area (217 mg kg^{-1} C-CO_2) than for the preserved Caatinga (190 mg kg^{-1} C-CO_2), showing an inverse pattern to the Alfisol (Table 4). In the external mycelium of the arbuscular mycorrhizal fungi (AMF), a glycoprotein is produced (Driver et al., 2005), generally called glomalin, which together with the hyphae screen in the soil increases particle aggregation, soil aggregate stability, and carbon stock (Rillig et al., 2001), contributing to the improvement of soil quality.

The eigenvalues for the two canonical variates based on the physical, chemical, and biological soil properties indicated that CAN1 explained most of the variation of the studied cases (0.60), whereas CAN2 explained only 0.14. The canonical correlation, which measures the degree of correlation between sets of variables, the F-value, and the p-value were higher for CAN1 than for CAN2. Wilk's Lambda multivariate test revealed no significant differences between the different soils/areas/strata (Table 5).

The standardized canonical coefficients for both canonical variates are summarized in table 3. A higher canonical coefficient indicates that a given variable is more important to the derivation of the canonical variate. The highest canonical coefficient for Can1 was observed for $Ca^{2+}$and Mg^{2+}, combined (14.682), which was one of the chemical properties with the highest potential for discrimination between the studied cases. This finding is

Table 4. Biological properties of an Alfisol and an Entisol of the Seridó Desertification Region, Parelhas, Rio Grande do Norte, from the preserved Caatinga (strata: catingueira, jurema, marmeleiro, and between trees), the recovery area with jurema (strata: jurema and between trees), and the degraded area without plant cover, at layer of 0.00-0.10 m, in the dry period

Soil	Area	Glomalin	Microbial biomass carbon	Microbial respiration
		g	mg kg^{-1}	
Alfisol	Preserved Caatinga	5.2 Aa	49.0 Aa	212 Aa
	Recovery area	3.0 Aa	51.8 Aa	169 Aa
	Degraded area	2.8 Aa	46.6 Aa	185 Aa
Entisol	Preserved Caatinga	5.8 Aa	74.9 Aa	190 Aa
	Recovery area	4.3 Aab	66.3 Aa	217 Aa
	Degraded area	2.7 Ab	57.5 Aa	149 Aa
CV (%)		41.55	61.20	45.92

Glomalin was extracted by the method of Wright and Upadhyaya (1996); microbial biomass carbon = fumigation-extraction method, according to Vance et al. (1987); microbial respiration = assays were processed according to Vance et al. (1987). For each column, means followed by the same capital letter, between soils for each area, and followed by a lower-case letter, between areas for each soil, did not differ statistically by the Tukey test, at the 5 % probability level. CV = coefficient of variation.

Table 5. Summary of the canonical variate analysis of the physical, chemical, and biological properties of an Alfisol and an Entisol from the preserved Caatinga (strata: catingueira, jurema, marmeleiro and between trees), the recovery area with jurema (strata: jurema and between trees), and the degraded area without plant cover

Condition	VC	Canonical correlation	Adjusted canonical correlation	Eigenvalue	Proportion	Cumulative	Approximate F Value	Num. df	Den. df	Pr> F
Soil-Area-Strata	1	0.990956	0.983962	54.5364	0.6041	0.6041	1.74	260	133.74	0.0002
	2	0.963775	0.933387	13.0571	0.1446	0.7487	1.32	228	131.71	0.0381
			Statistic	Value	F Value	Num. df	Den. df	Pr> F		
			Wilks' Lambda	0.00000010	1.74	260	133.74	0.0002		

EigenvaluesInv (E) *H = CanRsq/(1-CanRsq) Test of H_0: the canonical correlations in the current row and all that follow are zero; VC = canonical variable.

in accordance with that of Galindo et al. (2008), who studied the complete removal of the A horizon due to erosion in some of the most severely degraded semiarid areas of Jataúba, Pernambuco State (PE), Brazil.

The chemical properties of sulfates and the combined H and Al content were also relevant for Can1. Clay dispersion and MWD stood out amongst the physical properties, and glomalin was the most important biological parameter for CAN1. Interestingly, calcium (-11.573) and magnesium (-10.919), separately, were suppressor variables and had little potential for discrimination between the studied cases (Table 6).

The mean canonical variate scores showing dispersion and the formation of groups of different soil, area, and stratum combinations are shown in figure 1. Two different groups were identified located to the left and right of CAN1 = 0. With one exception (NCJur), this division separated the two soil types. The group with CAN1> 0 was further divided into two subgroups: one constituted by NCCat, NCMar, ND, and NRJur and another constituted by NRbt and NCbt (Figure 1).

Regardless of the soil type, the preserved Caatinga exhibited higher OC contents and CEC, which are associated with higher combined Ca^{2+} and Mg^{2+} levels; these contents physically affect aggregate stability and MWD. This higher C input to the soil was probably due to the growth of grasses, which have short life cycles and contribute

Table 6. Standardized canonical coefficients of the physical, chemical, and biological properties of an Alfisol and an Entisol from the preserved Caatinga (strata: catingueira, jurema, marmeleiro and between trees), recovery area with jurema (strata: jurema and between trees), and degraded area without plant cover

Properties	Soils, areas, and strata	
	CAN1	CAN2
Glomalin	1.385	0.325
MBC	0.940	0.797
Basal respiration	-0.143	0.521
Clay dispersion	2.383	-1.676
Degree of flocculation	-0.138	-1.927
Soil density	-0.435	-0.926
Total porosity	-2.364	-1.072
MAD	2.087	-1.181
AGREGSTA	0.141	0.553
pH	1.884	-0.183
P	-0.015	-0.885
K^+	-0.298	-0.391
Na^+	-0.723	0.155
Ca^{2+} and Mg^{2+}	14.682	-5.128
Ca^{2+}	-11.573	6.621
Mg^{2+}	-10.919	5.387
H and Al	2.159	-4.225
C	0.804	0.637
Sulfur	2.455	-0.529
SB	0.000	0.000
CEC	0.000	0.000
V	2.306	-6.280

MBC = microbial biomass carbon; MAD = mean aggregate diameter; AGREGSTA = aggregate stability; SB = sum of bases; CEC = cation exchange capacity; V = base saturation. CAN1 and CAN2 = first and second canonical variates.

to a significant increase in the C content, especially due to the decomposition of fine roots (Martins et al., 2010).

The group with CAN1< 0 was also divided into two subgroups: one formed by the strata NCJur, LCCat, LCMar, LCJur, and LRJur and one formed by LCbt, LRbt, and LD (Figure 1).

The dispersion and formation of the subgroups of both groups (to the left and right of CAN1 = 0) were affected by other properties with the potential to discriminate between the studied cases in addition to the canonical coefficients of the previously mentioned physical, chemical, and biological properties. The first subgroup (CAN1>0) was affected by glomalin (biological property) and followed by MBC; the second subgroup (CAN1>0) was affected by clay dispersion (physical property) and base saturation (chemical property). The group dispersion and formation of the first subgroup (CAN1<0) were also affected by the combined Ca^{2+} and Mg^{2+} contents, whereas the second subgroup (CAN1<0) was affected by bulk density and total soil porosity (physical property).

Regarding the biological soil activities, a positive effect was observed for all properties (i.e., higher glomalin, MBC, and microbial respiration). Under the studied conditions, there is a constant supply of decomposing organic material, which keeps the soil covered, with lower temperature variation and moisture levels that are more adequate. The higher

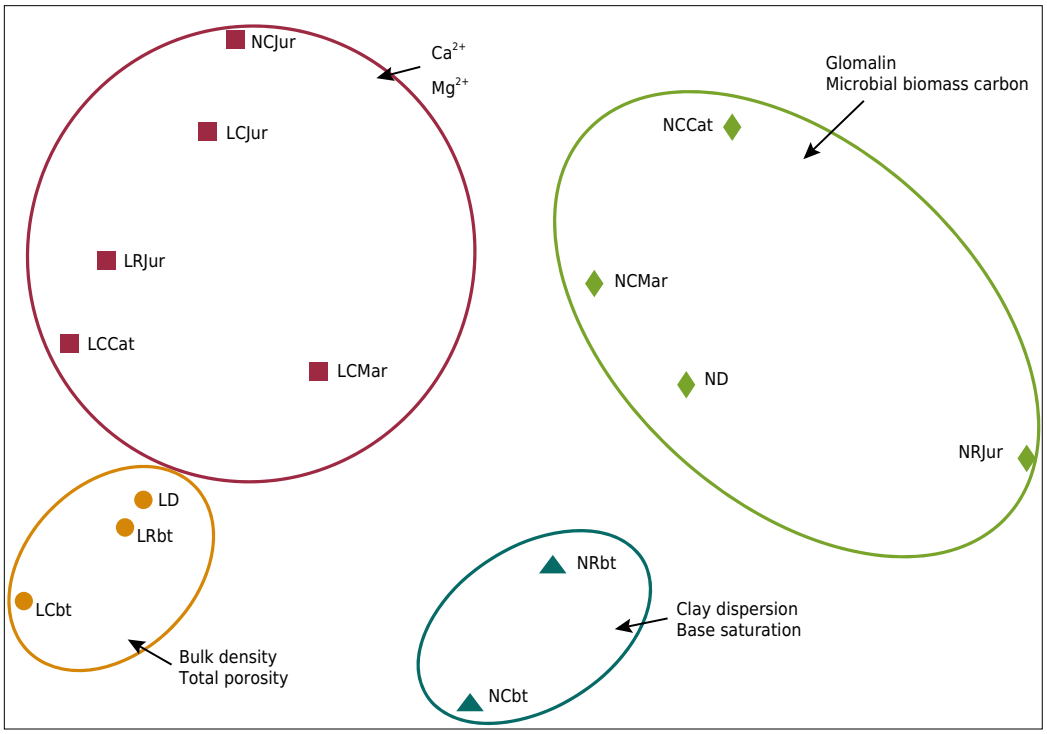

Figure 1. Distribution of the different strata for the two studied soils based on the scores for two canonical variates (CAN1 and CAN2), including physical, chemical, and biological properties. LCCat = Alfisol Caatinga area, stratum catingueira; LCMar = Alfisol Caatinga area, stratum marmeleiro; LCJur = Alfisol Caatinga area, stratum jurema; LCbt = Alfisol Caatinga area, stratum between trees; LRJur = Alfisol recovery area, stratum jurema; LRbt = Alfisol recovery area, stratum between trees; LD = Alfisol degraded area; NCCat = Entisol Caatinga area, stratum catingueira; NCMar = Entisol Caatinga area, stratum marmeleiro; NCJur = Entisol Caatinga area, stratum jurema; NCbt = Entisol Caatinga area, stratum between trees; NRJur = Entisol recovery area, stratum jurema; NRbt = Entisol recovery area, stratum between trees; ND = Entisol degraded area.

content of microbial biomass was positively related to CO_2 release. Basal respiration was directly related to the quantity of the soil organic carbon, which was higher under these conditions, and was also related to the MBC.

CONCLUSIONS

The changes in soil use affected the set of properties measured in the different areas sampled, because the soil fertility is altered, and mainly has low levels of phosphorus and organic matter, which may negatively influence the establishment of vegetal cover and particularly affect the resilience of degraded areas.

The type of use found in the preserved Caatinga, even though it has not undergone anthropic interference in the last twenty years, also showed a stability of aggregates similar to the other areas studied, but with a lower soil density.

Variation in the different parameters measured was not very high despite the different situations studied. However, the canonical analysis resulted in the formation of four subgroups using two canonical variates, with contributions of two chemical properties (combined Ca^{2+} and Mg^{2+} and sulfates), two physical properties (clay dispersion and MWD), and one biological (glomalin) property. According to the canonical analysis, the CAN1 soil type was the most important factor for the differentiation of the two main groups.

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