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Geostatistical and multivariate analysis of soil attributes between terrace channels in the semi-arid region[1]

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ABSTRACT - The spatial variability of soil attributes in terraced areas is poorly studied in the semi-arid region. Considering that multivariate analysis enhances the diagnosis of spatial variability from geostatistics, soil attributes were studied in different zones between terrace channels in semi-arid region, more precisely in a retention terrace area in Canindé (Ceará, Brazil). Soil samples (n = 100) were collected at depths of 0.0 - 0.1 and 0.1 - 0.2 m for descriptive and geostatistical analysis. For multivariate analysis, samples from three zones relative to the terrace channel (Upper, Middle, and Lower) in the 0.0 - 0.2 m layer were considered, with 30 replicates. There was spatial dependence of soil attributes in the two layers studied. Near the channel, in the respective layers, there was higher clay content (13.7% and 14.7%) and higher degree of flocculation (61.3% and 71.7%) compared to the other zones. Water-dispersible clay was higher in the Upper zone (6.5% and 7.7% in the respective layers), while the Middle zone showed higher potential acidity in the evaluated layers (4.8 and 4.5 $cmol_c\ dm^{-3}$, respectively) compared to the other zones. In the multivariate analysis, there were highlights for the higher sum of bases in the Upper zone (18.9 ± 0.8 $cmol_c\ dm^{-3}$), higher sand content in the Middle zone (72.6 ± 0.6%), lower potential acidity (2.1 ± 0.2 $cmol_c\ dm^{-3}$) and higher phosphorus content (12.8 ± 3.0 mg kg^{-1}) in the Low zone. The zone above the terrace channel loses mainly clay and requires practices to increase water and nutrient retention.

Key words: Soil erosion. Terraces. Soil conservation. Deposition zones. Loss zones.

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INTRODUCTION

Erosion degrades agricultural land, posing a threat to food production and sustainable development (FAO, 2019; Yin; Zhao; Pereira, 2022). In the Brazilian semi-arid region, there are soils with high susceptibility to erosion whose degradation is intensified when subjected to inadequate management practices (Santos *et al*., 2017). In this scenario, soil and water conservation practices are essential to enable food production without depleting natural resources.

Terraces are examples of mechanical conservation practices, characterized by structures composed of the combination of channel and ridge, built transversely to the slope to segment the length of the hillside and reduce surface runoff and soil transport (Damene; Tamene; Vlek, 2012; Morgan, 2005). By reducing surface runoff and increasing water infiltration into the soil, terracing contributes to coexistence with the semi-arid region and improves conditions for agriculture (Mesfin *et al*., 2018; Wolka *et al*., 2022)

The presence of sediment loss and deposition zones between terraces increases the spatial variability of soil physical and chemical attributes (Amare *et al*., 2013; Wolka *et al*., 2022). Variation in the contents of organic matter, nutrients and particle-size fractions can result in sites in the agricultural area with higher soil fertility and moisture, influencing the development, stability and yield of crops (Mesfin *et al*., 2018, 2019; Wolka *et al*., 2022). Such variability in soil attributes in terraced areas can be used in favor of farmers in the search for the sustainability of agricultural production in dry regions (García-Palacios *et al*., 2019). Knowledge on the spatial variation of soil attributes allows input application to be more precise, with adjustments in the distribution and quantities based on soil fertility (Wolka *et al*., 2022).

Studies on the spatial variability of soil physical and chemical attributes not only in semi-arid regions of Brazil and the world, but also under other edaphoclimatic conditions, have been carried out with emphasis on different soil types and management practices, adopting geostatistical analysis tools (Araújo *et al*., 2018; Queiroz *et al*., 2020; Selmy *et al*., 2022; Silva; Manzione; Oliveira, 2023). However, no studies were found aimed at investigating variations that occur as a function of the terracing practice in areas of family farming, especially with the multivariate analysis approach. This is a useful tool for studies related to soil management, as it considers the relationships between variables and avoids misinterpretations (Reichert *et al*., 2022). The multivariate approach provides more accurate information compared to classical statistical methods and allows for more consistent interpretations for later definition of use and management practices (Carvalho *et al*., 2018; Hair Jr. *et al*., 2009).

The present study is based on the hypothesis that geostatistical and multivariate data analysis approaches allow the identification of significant variations in the distribution of soil attributes between terrace channels, helping to define management strategies in family farming areas under the edaphoclimatic conditions of the semi-arid region. The objective of this study was to analyze the physical and chemical attributes of the soil in different positions between terraces, evaluating them by means of geostatistics and multivariate statistics.

MATERIAL AND METHODS

Location and description of the study area

The study was carried out in 2017, in Canindé (CE, Brazil), more precisely at the geographic coordinates 4°37’39” South latitude and 39°23’15” West longitude (Figure 1A).

The climate of the region is BSw’h’ (hot and semi-arid), according to Köppen’s classification, with average temperature of 24 °C and possibly reaching 34 °C. Average annual rainfall in the region is around 671 mm, with rains concentrated in the period from February to April, which may extend until May (FUNCEME, 2010, 2022). In the year in which the study was conducted, the local rainfall observed (616.7 mm) was below the annual average for the region (Figure 2).

The local relief is characterized by residual massifs and Sertaneja depressions, with a predominance of open and/or dense shrubby Caatinga vegetation and semi-deciduous tropical rainforest (IPECE, 2017). The soil of the study area is a *Luvissolo* (Alfisol) (FUNCEME, 2010; Santos *et al*., 2018).

Description of the terraces and management in the study area

Retention terraces were built in the study area in 2006, with horizontal spacing ranging from 15 to 20 meters and occupying an area of 5.0 ha, whose slope varies from 9 to 16%. After terracing, the area was cultivated for four successive years without the adoption of other conservation practices, using fire in the preparation of the area for subsequent intercropping of maize (*Zea mays* L.) and cowpea (*Vigna unguiculata* L.). At the time of the collection of soil samples, approximately 70% of the terraced area had been fallow for about six years, with Caatinga vegetation at different levels of regeneration.

Sample collection and analytical procedures

Soil sampling was carried out in an area with dimensions of 18.0 x 45.0 m, totaling 810 m^2 located between two terrace channels. The sampling grid was established with points spaced every two meters in width and every five meters in length, totaling 100 points. Sequentially numbered markers were placed at the intercession points of the grid corresponding to the sampling points to facilitate localization and sampling. Subsequently, the points were georeferenced using Garmin eTrex 10 GPS navigation system. For physical and chemical analyses, disturbed soil samples were collected at 100 points and in two layers (0.0 to 0.1 m; 0.1 to 0.2 m) for detailing the possible differences, totaling 200 samples.

Figure 1 - Location of the study area, including the state of Ceará in the northeastern region of Brazil (A), the municipality of Canindé in the state of Ceará (B) and the geographic coordinates of the study area in the district of Iguaçu, Canindé, CE, Brazil (C)

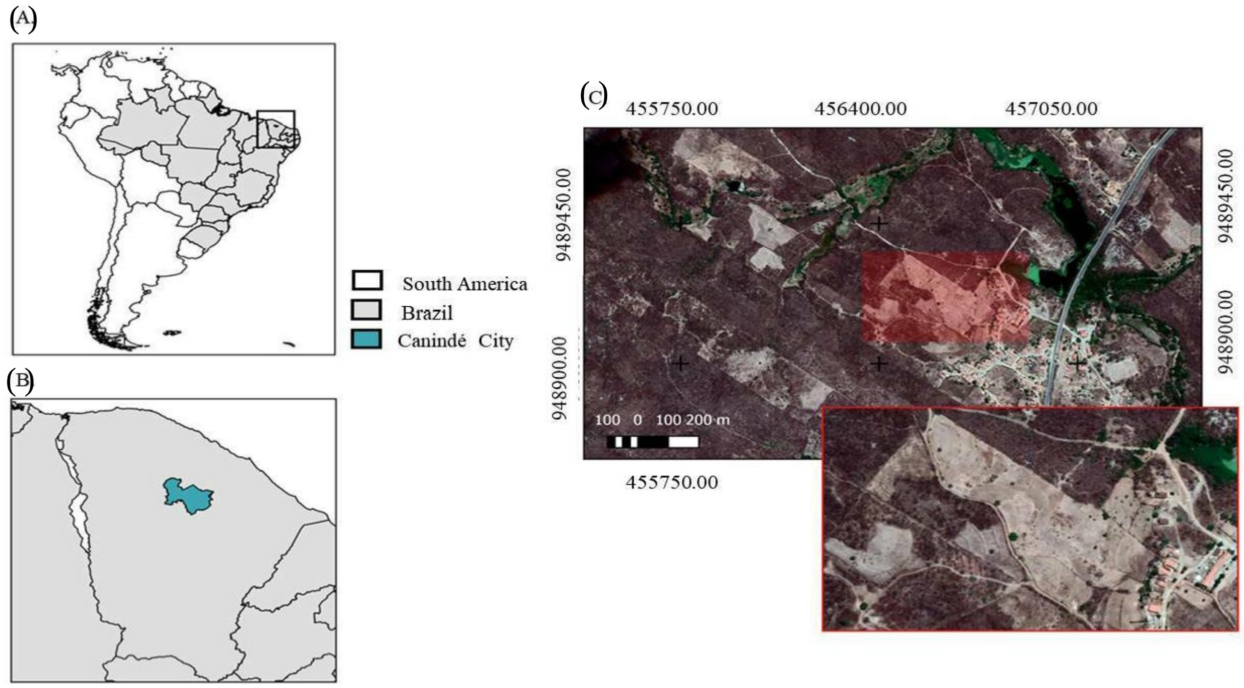
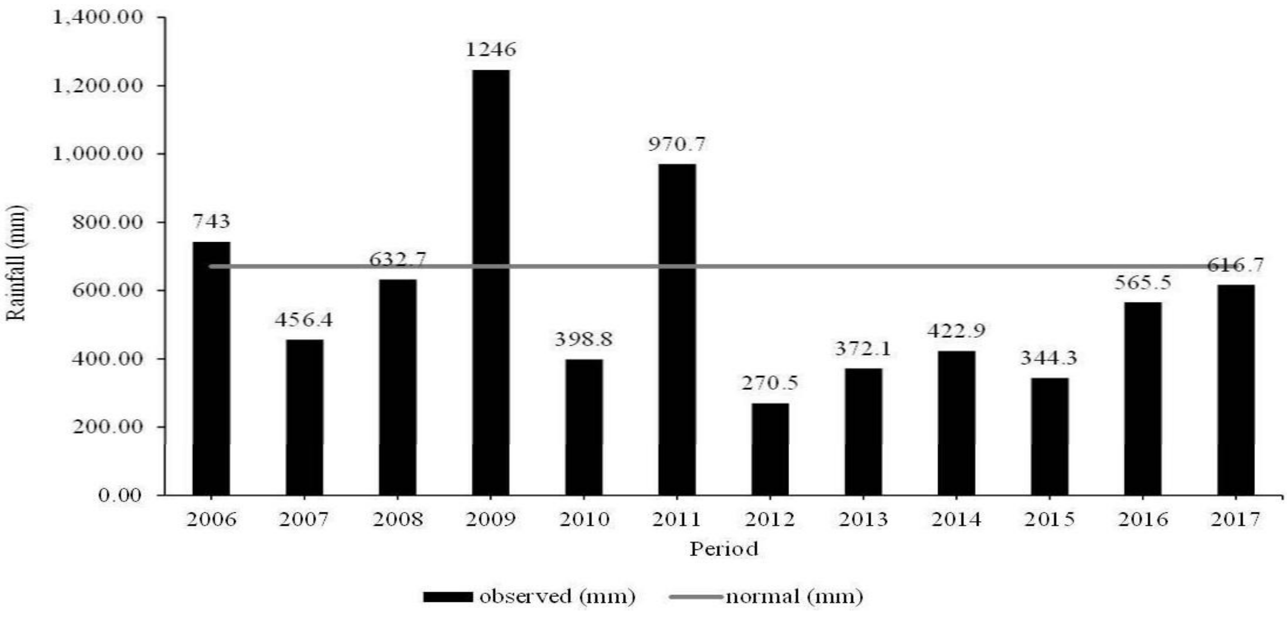


Figure 2 - Expected and observed average annual rainfall from 2006 to 2017 in the region of Canindé (CE, Brazil) where this study was conducted



For multivariate analysis, samples were collected in three positions relative to the terrace channel (Upper, Midd and Lower), in the 0.0 – 0.2 m layer (Figure 3A, B, C, D), given the relevance of the first 0.2 m of soil depth for the growth of roots of plants cultivated in the region, such as maize (Costa; Coutinho, 2022). Samples from 30 points in each position were considered (Figure 3B), constituting the replicates and totaling 90 samples (n = 90). The Lower, Midd and Upper positions were defined considering distances from 0.0 to 6, 6.0 to 12 and 12 to 18 meters, respectively, relative to the terrace channel. In the Lower position, the sampling point was close to the channel, and in the Upper position, the samples were collected just below the ridge (Figure 3).

The collected soil was packed in identified plastic bags and transported to the laboratory where it was air-dried. After drying, the samples were pounded to break up clods and passed through a 2-mm-mesh sieve to perform the analyses and determine the following physical and chemical attributes: particle size (sand, silt, clay and sand fractions), water-dispersible clay (WDC), degree of flocculation (DF), pH, potential acidity (H + Al), total organic carbon (TOC), phosphorus (P – Mehlich-1 extractant), potassium (K), calcium (Ca), magnesium (Mg) and sodium (Na). The following attributes were also calculated: sum of bases (SB), cation exchange capacity at pH 7.0 (CEC), exchangeable sodium percentage (ESP) and base saturation (V%). Laboratory analyses were performed according to procedures described in Teixeira *et al*. (2017).

Descriptive analysis

Mean, median, standard deviation, coefficient of variation, maximum value, minimum value, skewness and kurtosis coefficient were calculated. The data were related to distances referring to the coordinates for performing the geostatistical analysis.

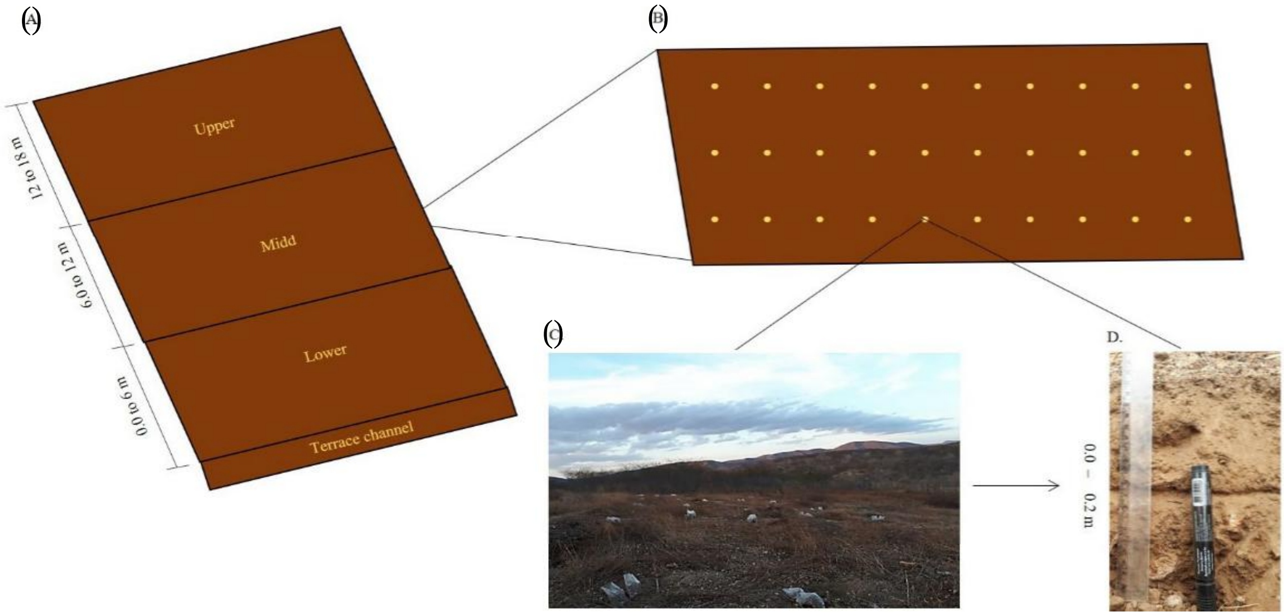
Geostatistical analysis

Semivariograms were constructed to assess the spatial dependence, considering that the semivariance of a regionalized variable is expressed as:

$$\hat{Y}(h)=\frac{1}{2N(h)}\sum_{i=1}^{N(h)}\left[Z(x_i)-Z(x_i+h)\right]^2 \qquad (1)$$

Where N (h) expresses the pairs of measured values [Z(xi) – Z(xi + h)], separated by the distance h (Vieira, 2000). GS+ software (Robertson, 2008) - Free version - was used to fit the semivariograms to the theoretical models that best explained the existing variability and its importance for data interpolation by the kriging method (Isaaks; Srivastava, 1989). To fit the semivariograms to the models, values of semivariance (γ (h)), nugget effect (C_0), partial sill (C), maximum distance from the definition of the semivariogram (d) and range (a) were obtained (Manzione, 2002). The linear model without sill does not have the parameter C, allowing the interpolation process even without establishing the limit, in this case, the parameters A and B are the constants that define the model (Yamamoto; Landim, 2013).

Figure 3 - Schematic representation of the positions relative to the terrace channel (A), collection points at each position (B), arrangement and depth of collection of soil samples in the field (C and D)



The spatial dependence index (SDI) was calculated by the relationship between the nugget effect (C_0) and the sill ($C + C_0$). This index was used to make the classification, which establishes weak SDI when the ratio is equal to or less than 25%; moderate SDI when the ratio is greater than 25% and less than 75%; and strong SDI when this ratio is greater than 75% (Manzione, 2002). To visualize the distribution and variability of the analyzed variables, maps were constructed using the Kriging method in GS+ software - free version (Robertson, 2008).

Multivariate statistical analysis

SAS statistical program (SAS Institute, 2012) was used to check multivariate normality, homogeneity of variances, and discrepant points using the Shapiro-Wilk test, Levene test, and Student's t-test, respectively. In order to identify whether the soil attributes show statistical differences between the sampling positions, the mean vectors of the response variables were compared by multivariate analysis of variance (MANOVA).

Principal component analysis (PCA) was performed to characterize the terraced area in terms of fertility and to reduce the number of variables studied to a few indices that explain most of the data variability. The dataset composed of the values of the soil attributes in each position between the terrace channels was standardized ($\mu = 0$; $\sigma^2 = 1$) to eliminate the influence of the different units of measurement of the variables on the result. The criterion for choosing the number of components was to select those that had eigenvalues greater than one (Manly; Alberto, 2019).

From the dataset with the replicates (n = 90), analysis of the canonical discriminant function was performed to check whether there is a difference/separation in the soil attributes according to the position between the terrace channels. The PROC CANDISC procedure of SAS/STAT was used as a dimension reduction technique. This procedure allows finding linear combinations of the original variables (canonical variables) that discriminate the evaluated parameters that most contributed to the difference or separation in soil attributes as a function of the evaluated position (Manly; Alberto, 2019). In this case, the two best dimensions were analyzed by canonical variables 1 and 2 (CAN1 and CAN2). Similarity of the positions between terrace channels was assessed using the hierarchical method of mean group linkage (UPGMA) measured by the Euclidean distance for cluster analysis.

RESULTS AND DISCUSSION

Descriptive analysis

The average contents of sand, silt and clay (in percentage) were, respectively, 73.7, 18.9 and 7.4 in the 0.0 to 0.1 m layer and 70.0, 21.2 and 8.7 in the 0.1 to 0.2 m layer, resulting in a medium-sandy texture in both layers (Table 1). Both layers correspond to the A horizon of the soil of the study area, not reaching the subsurface horizon, which shows the increase of clay in subsurface that characterizes the textural B horizon of *Luvissolos* (Alfisols) (Santos *et al*., 2018). The sand fraction consisted of 48.5% and 50.6% of fine sand in the layers of 0.0 to 0.1 and 0.1 to 0.2 m, respectively. After the clay and silt fractions, fine sand can be considered the fraction most easily transported by flows that may occur between terrace channels when compared to medium and coarse sand (Bertol; Cassol; Barbosa, 2019). Water-dispersible clay (WDC), whose average values ranged from 4.0 to 4.8% in the layers evaluated, represents suspended unit particles that are highly susceptible to being transported by runoff (Bertol; Cassol; Barbosa, 2019).

The mean values of the chemical attributes pH, H + Al, V% and CEC were consistent with the *Luvissolo* (Alfisol) class (Table 1), reflecting the lower active and potential acidity and the higher values of CEC and V% associated with the lower degree of soil weathering (Santos *et al*., 2018). P and TOC contents were higher in the 0.0 to 0.1 m layer (16.1 mg kg^{-1} and 9.0 g kg^{-1}, respectively) and lower in the 0.1 to 0.2 m layer (7.4 mg kg^{-1} and 6.1 g kg^{-1}, respectively), which is related to the higher accumulation of organic matter in the first layer compared to the second one (Araújo *et al*., 2018).

The P content showed coefficients of variation (CV) of 83.3% and 152.7% in the 0.0 to 0.1 and 0.1 to 0.2 m layers, respectively, which are considered high (Warrick; Nielsen, 1980). As the studied area does not receive fertilization (mineral or organic), the variability observed for P content may be due to the fallow period, which allowed the presence of distinct species of regenerating vegetation randomly distributed in the area, with variable constitution and nutritional requirements (Nascimento *et al*., 2018). High variability of P content in the soil has been observed in pasture area (Wang; Zhang; Huang, 2009), and it can be explained by the presence of animals, which expel excrement randomly, bringing variation to P content in the soil (Costa *et al*., 2014; Liu; Zhou, 2017; Schnyder; Locher; Auerswald, 2010).

Mean and median values were close for the physical and chemical attributes in the two layers studied, except for P contents. Similar values of mean and median, as well as kurtosis and skewness coefficients close to zero, are indicative of the normal distribution and suitability of the data for geostatistical analysis (Zanão Júnior *et al*., 2010).

Geostatistical analysis

Different values of the nugget effect (C_0) and sill (C_0 + C) indicate that the evaluated attributes showed spatial dependence in the two layers evaluated (Table 2).

The spatial dependence index (SDI) ranged from medium to strong, representing a good spatial dependence structure of the sampled points (Araújo *et al.*, 2018). In the 0.0 to 0.1 m layer, the sand, coarse sand and silt contents, the degree of flocculation and pH, V% and CEC values were described by the exponential model; contents of medium sand, clay and water-dispersible clay were described by the Gaussian model; while the values of H + Al, P and TOC were described by the spherical model (Table 2). In the 0.1 to 0.2 m layer, the contents of coarse sand, fine sand, water-dispersible clay, the values of the degree of flocculation, pH, P and TOC contents were described by the exponential model; sand and medium sand contents were described by the Gaussian model; while silt, clay, and H + Al, V% and CEC values were described by the spherical model (Table 2).

Table 1 - Descriptive statistics of physical and chemical attributes of soil samples collected between terraces, in the layers of 0.0 to 0.10 m and 0.10 to 0.20 m

Attribute	Min	Max	Mean	Median	SD	CV	Skew.	Kurt.
				0.0 – 0.1 m (n = 100)				
Sand (%)	61.9	85.7	73.7	74.3	3.7	5.0	-0.5	1.8
CS (%)	22.4	46.3	30.8	30.5	4.1	13.4	0.3	2.4
MS (%)	17.4	23.8	20.7	20.3	1.4	6.6	0.7	0.1
FS (%)	33.6	57.1	48.5	48.8	4.2	8.7	-0.2	2.7
Silt (%)	10.6	24.9	18.9	18.9	2.7	14.1	-1.8	0.5
Clay (%)	2.4	17.1	7.4	6.9	2.7	36.2	2.4	1.8
WDC (%)	0.9	7.7	4.0	3.6	1.7	42.3	-1.7	-0.4
DF (%)	7.0	85.3	45.8	47.5	18.3	39.8	3.8	-1.0
pH	5.6	7.1	6.2	6.2	0.2	3.3	0.2	4.4
H + Al ($cmol_c\ dm^{-3}$)	1.0	5.3	2.9	2.8	1.0	36.0	0.2	-0.7
V (%)	69.5	95.5	87.0	87.6	4.7	5.5	-0.4	1.5
CEC ($cmol_c\ dm^{-3}$)	14.9	36.4	22.2	22.6	3.9	17.4	-0.3	0.9
P ($mg\ kg^{-1}$)	2.5	63.6	16.1	10.6	13.4	83.3	1.2	2.1
TOC ($g\ kg^{-1}$)	3.4	29.6	9.0	8.4	3.4	37.8	0.5	14.1
				0.1 – 0.2 m (n = 100)				
Sand (%)	34.4	81.8	70.0	70.4	5.3	7.6	-0.3	21.1
CS (%)	19.5	43.3	27.9	27.9	3.0	10.6	0.0	7.0
MS (%)	18.3	24.8	21.5	21.6	1.3	6.0	-0.3	0.0
FS (%)	34.6	60.1	50.6	50.3	3.1	6.2	0.4	6.5
Silt (%)	6.6	52.5	21.2	21.7	4.9	23.1	-0.3	18.6
Clay (%)	4.1	15.7	8.7	8.5	2.3	26.1	0.3	0.9
WDC (%)	1.0	9.3	4.8	4.5	1.5	32.0	0.5	0.9
DF (%)	4.9	84.9	43.2	42.7	17.1	39.5	0.1	-0.3
pH	6.0	7.1	6.4	6.4	0.2	3.5	0.0	0.1
H + Al ($cmol_c\ dm^{-3}$)	0.5	5.1	2.6	2.5	1.0	38.8	0.4	-0.6
V (%)	69.8	97.8	86.5	87.3	5.3	6.1	-0.5	0.0
CEC ($cmol_c\ dm^{-3}$)	13.7	26.0	19.6	19.7	2.8	14.5	-0.2	-0.9
P ($mg\ kg^{-1}$)	0.1	60.5	7.4	2.4	11.3	152.7	1.3	7.1
TOC ($g\ kg^{-1}$)	1.3	13.7	6.1	5.9	2.3	37.6	0.3	1.6

CS - Coarse Sand; MS - Medium Sand; FS - Fine Sand; WDC - Water-Dispersible Clay; DF - Degree of Flocculation; V – Base saturation; CEC – Cation Exchange Capacity; P – Phosphorus; TOC – Total Organic Carbon; Min - minimum; Max - Maximum; SD - Standard Deviation; CV - Coefficient of Variation; Skew. - Skewness; Kurt - Kurtosis

The range varied from 2.9 to 153 m in the 0.0 to 0.1 m layer, with the lowest value for soil pH and the highest value for coarse sand content (Table 2). In the 0.1 to 0.2 m layer, the range varied from 3.5 to 43 m, with the lowest value for soil CEC and the highest value for fine sand content (Table 2). Range represents the maximum distance that an attribute correlates spatially, so sampling distances greater than those indicated in the range result in random distribution (Zanão Júnior *et al*., 2010).

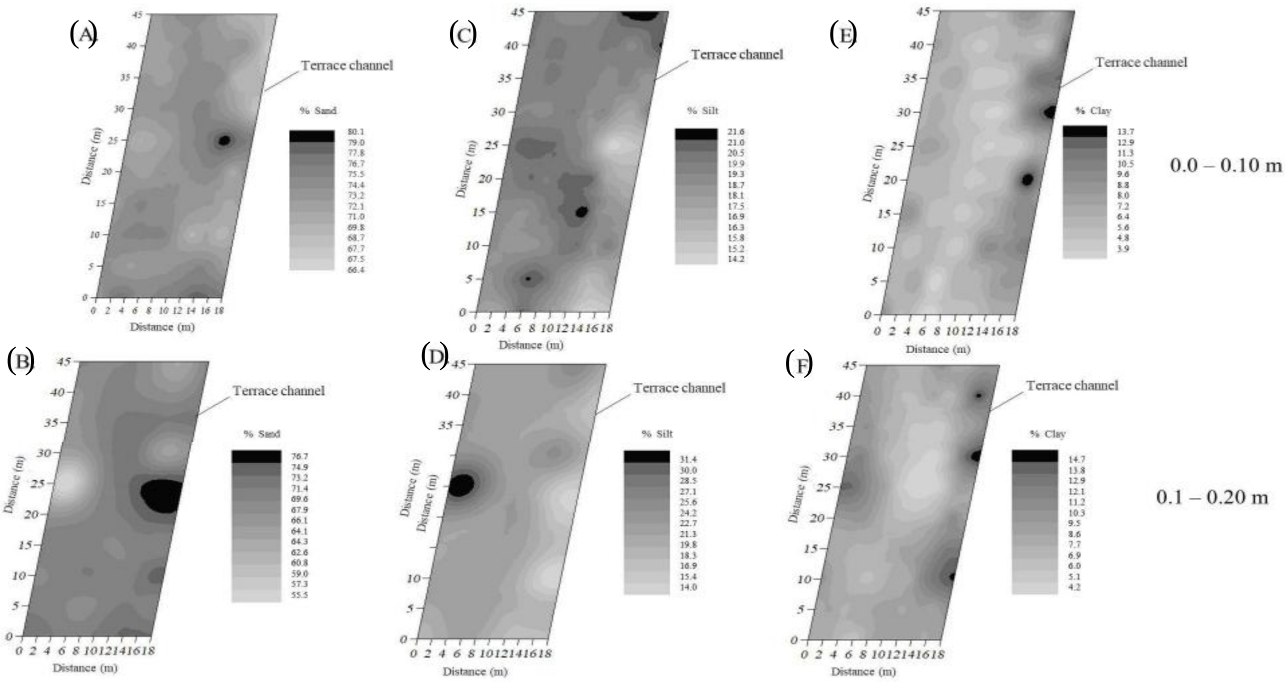
Maps of spatial distribution of the physical attributes of the soil showed a higher clay content near the terrace channel, with values of 13.7% and 14.7% in the 0.0 to 0.1 and 0.1 to 0.2 m layers, respectively. In the positions above the channel, these contents were lower, with values of 3.9% and 4.2% in the two layers mentioned (Figure 4E, F). For the sand fractions, there was an accumulation of medium sand in the first 10 m of the channel length (Figure 5C, D). There was no accumulation of fine sand close to the channel, but in the upper position, at 35 – 45 m in its length (Figure 5E, F).

Table 2 - Skewness and kurtosis of the data, models and parameters of the semivariograms for the physical attributes of the soil collected between terraces, in the layers of 0.0 to 0.10 m and 0.10 to 0.20 m

Attribute	Model	Nugget Effect (C_0)	Sill (C_0 + C)	Range (m)	C/(C_0 + C)[1] (%)	SDI[2]
0.0 – 0.1 m (n = 100)						
Sand	Exponential	6.5	15.8	25.9	58.8	Moderate
CS	Exponential	2.6	29.6	153.0	91.2	Strong
MS	Gaussian	1.1	2.2	20.8	50.0	Moderate
FS	Linear	6.9	18.2	22.7	62.0	Moderate
Silt	Exponential	4.1	8.2	25.1	50.0	Moderate
Clay	Gaussian	2.6	8.9	11.1	70.3	Moderate
WDC	Gaussian	0.5	3.2	10.1	82.4	Strong
DF	Exponential	240.5	485.4	66.7	48.3	Moderate
pH	Exponential	0.004	0.04	2.9	90.0	Strong
(H + Al)	Spherical	0.2	1.2	9.1	83.8	Moderate
V%	Exponential	7.8	23.0	7.4	66.0	Moderate
CEC	Exponential	5.6	16.2	8.1	65.7	Moderate
P	Spherical	34.9	178.8	7.7	80.5	Strong
TOC	Spherical	0.5	11.7	3.8	95.7	Strong
0.0 – 0.2 m (n = 100)						
Sand	Gaussian	19.4	38.7	21.3	49.8	Moderate
CS	Exponential	3.6	10.5	34.8	65.5	Moderate
MS	Gaussian	1.1	2.2	20.5	50.5	Moderate
FS	Exponential	5.0	12.3	43.3	59.6	Moderate
Silt	Spherical	0.5	6.5	10.0	92.5	Strong
Clay	Spherical	0.5	6.5	10.0	92.5	Strong
WDC	Exponential	1.1	2.7	14.2	60.5	Moderate
DF	Exponential	39.1	304.7	5.1	87.2	Strong
pH	Exponential	0.00	0.05	6.2	82.4	Strong
(H + Al)	Spherical	0.2	1.2	9.7	85.2	Strong
V%	Spherical	7.2	30.3	9.5	76.2	Strong
CEC	Spherical	1.8	6.9	3.5	73.3	Strong
P	Exponential	37.2	135.4	7.8	72.5	Moderate
TOC	Exponential	0.3	5.0	4.1	93.2	Strong

CS - Coarse sand; MS - Medium sand; FS - Fine sand; WDC - Water-dispersible clay; DF - Degree of Flocculation; [1] Degree of spatial dependence; [2]Spatial Dependence Index (Manzione, 2002)

Figure 4 - Spatial distribution of sand (A, B), silt (C, D) and clay (E, F) percentages of the soil collected between terraces, in the 0.0 to 0.10 m and 0.10 to 0.20 m layers



The higher percentage of clay near the terrace channel and the absence of fine sand accumulation in this position indicate that the runoff formed between terrace channels transported lighter and smaller particles (clay), but was not sufficient to transport sand particles (Bertol; Cassol; Barbosa, 2019). Transport of sand particles, especially fine sand, can occur with a greater slope (Wang *et al*., 2023) and is ultimately intensified by ramp length (Bertol; Cassol; Barbosa, 2019). Thus, the existence of terraces segmenting the slope is an important strategy to reduce the transport of fine sand.

The higher clay content near the terrace channel means that this zone is influenced by important aspects for agricultural cultivation in the semi-arid region, such as water retention and soil fertility (Artur *et al*., 2014; Kagabo *et al*., 2013; Li; Lindstrom, 2001; Mesfin *et al*., 2018; Wei *et al*., 2019). This study indicates that zones above the terrace channel need more emphasis on actions to increase organic matter content in order to increase soil water retention and minimize the effects of water deficit (Lal, 2020). However, the better distribution of fine sand in the terraced area may contribute to greater water retention, mitigating the effects related to lower clay content in areas with this condition (Parahyba *et al*., 2019).

Water-dispersible clay (WDC) was higher in the zone above the terrace channel, with values between 6.52% and 7.67% in the 0.0 to 0.1 and 0.1 to 0.2 m layers, respectively. The lowest WDC values (2.13% and 2.54%) were observed near the terrace channel in the two layers evaluated (Figure 6A, B). The higher WDC in the upper zone of the terrace channel represents soil particles that are easily transported to the lower zone as runoff is formed (Bertol; Cassol; Barbosa, 2019). The presence of the terrace channel is essential to contain this clay, preventing these particles from being transported to rivers and/or water reservoirs in the region (Figure 4E, F).

The degree of flocculation (DF) was higher in the area close to the terrace channel, with values of 61.3% and 71.7% in the 0.0 to 0.1 m and 0.1 to 0.2 m layers, respectively (Figure 6C, D). The lowest values were 22.1% and 16.2% in the two evaluated layers (Figure 6C, D). The higher DF in the area near the channel is associated with the accumulation of clay in this zone. The flocculation is due to the higher clay content that is associated with cations such as calcium, which has a greater flocculating effect compared to magnesium (Zhu; Marchuk; Bennett, 2020).

In the analysis of chemical attributes, higher potential acidity (H + Al) was found in the intermediate zone between terrace channels. The highest values (4.78 and 4.47 $cmol_c\ dm^{-3}$ in the 0.0 to 0.1 m and 0.1 to 0.2 m layers, respectively) occurred in the 0 to 10 m length range of the terrace channel (Figure 7C, D). This may be due to the greater removal of exchangeable bases (Ca, Mg, K) in this area, with hydrogen and aluminum remaining to constitute the potential acidity (Sousa; Miranda; Oliveira, 2007).

Figure 5 - Spatial distribution of coarse sand (%CS), medium sand (%MS) and fine sand (%FS) fractions of the soil collected between terraces, in the 0.0 to 0.10 m and 0.10 to 0.20 m layers

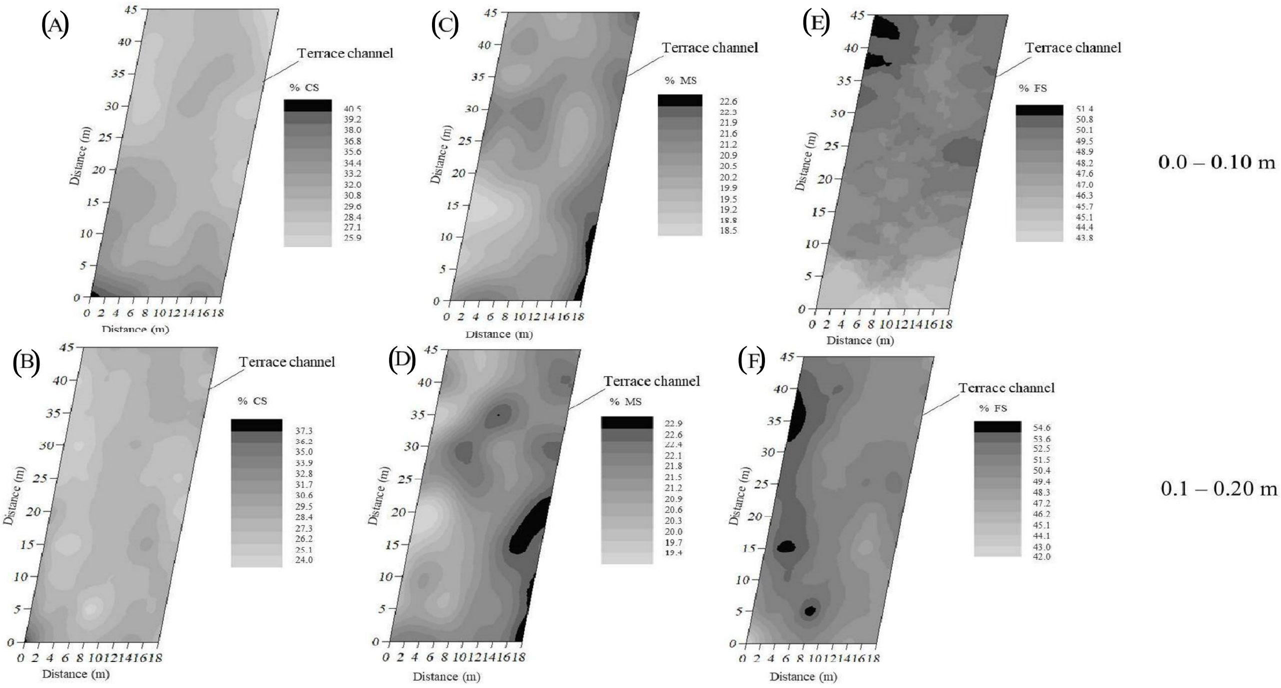


Figure 6 - Spatial distribution of water-dispersible clay - WDC (%) and degree of flocculation - DF (%) of the soil collected between terraces, in the 0.0 to 0.10 m and 0.10 to 0.20 m layers

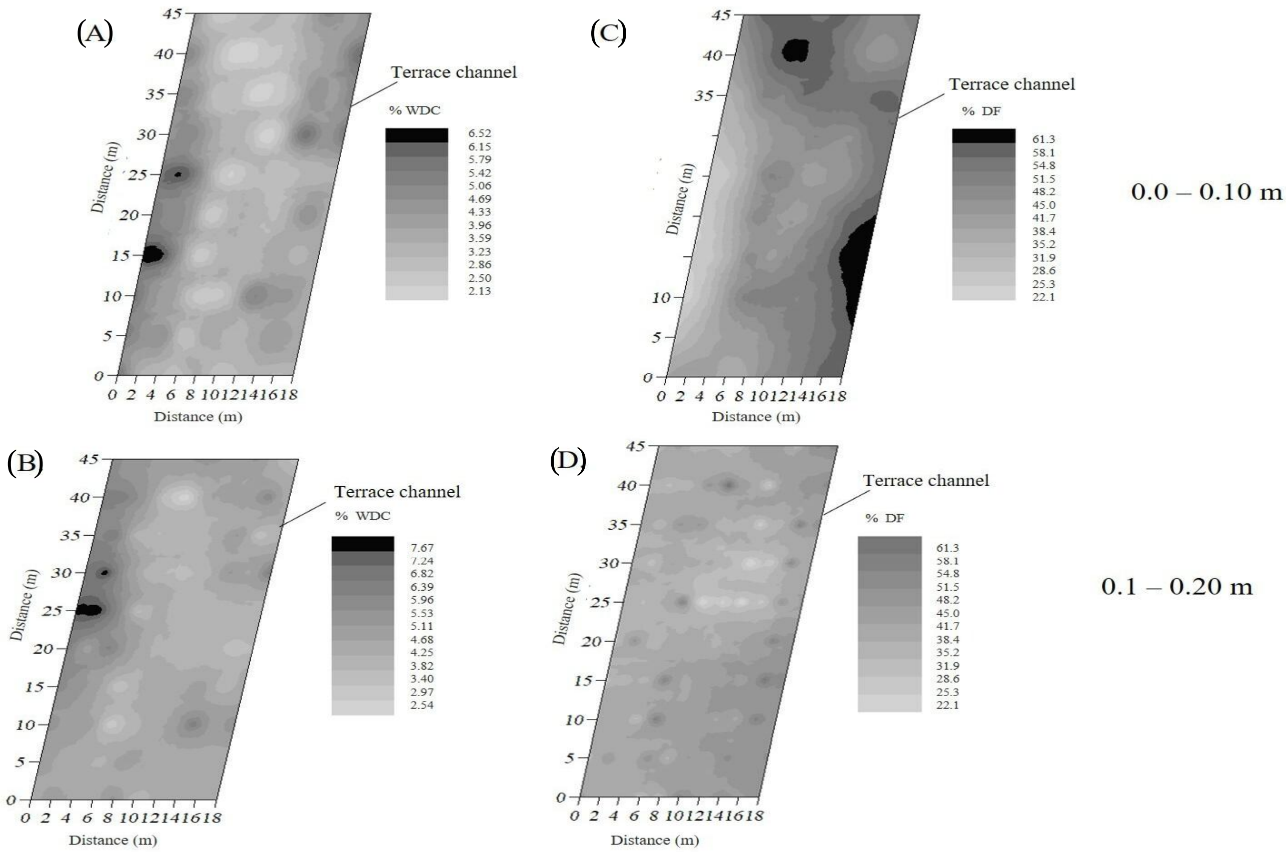
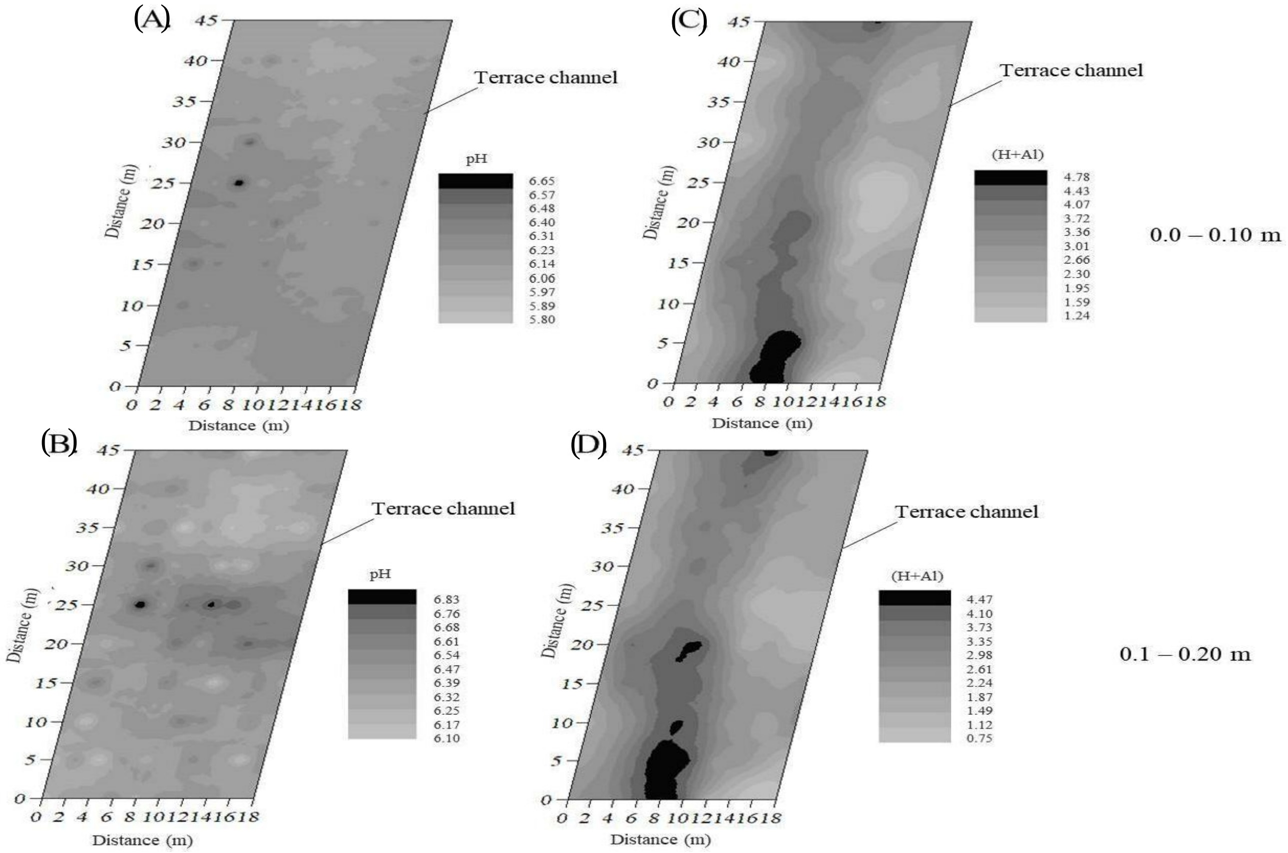


Figure 7 - Spatial distribution of the values of pH and potential acidity (H + Al – $cmol_c\ dm^{-3}$) of the soil collected between terrace channels, in the 0.0 to 0.10 m and 0.10 to 0.20 m layers



Base saturation (V%) reached values of 92.6 and 95.4% near the terrace channel in the 0.0 to 0.1 m and 0.1 to 0.2 m layers, respectively. This indicates less removal of exchangeable bases, as well as greater accumulation of bases coming from the zones above the channel (Figure 8A, B). Regarding the cation exchange capacity (CEC), higher values were observed near the terrace channel, especially in the 0.1 to 0.2 m layer (Figure 8C, D), which is associated with the higher clay content in this position.

Cation exchange capacity (CEC) was higher in surface, reaching maximum values of 30 $cmol_c\ dm^{-3}$ (Figure 8C, D). The higher CEC in surface is related to the presence of organic matter in this layer. Although the soil of the study area is poorly weathered and has high CEC values due to its mineralogy, its soil organic matter effectively contributes to increasing CEC in surface. However, in the present study, no higher TOC content was observed near the channel that could be associated with the CEC observed at this point (Figure 8G, H).

The highest P content was 55.3 mg dm^{-3} and was observed in the 0.0 to 0.1 m layer, with a specific position of accumulation in the intermediate zone between terrace channels, at 10 - 15 meters of channel length (Figure 8E, F). As already mentioned in the descriptive analysis, the points of higher P content may be associated with the regenerating vegetation in the area and the deposition of excrement from animals that grazed the area.

Multivariate analysis

The h_0 hypotheses of normality of residuals ($p = 0.91$) and homogeneity of variances ($p = 0.28$) were not rejected, and no discrepant points ($p > 0.05$) were found for the means of the physical and chemical attributes of the soil in the 0.0 to 0.2 m layer. The Upper, Midd and Lower positions, representing zones that were above, intermediate and closest to the terrace channel, differed in terms of the attributes studied ($p < 0.001$), considering the mean vectors of the physical and chemical attributes simultaneously (Table 3).

Two principal components (PC1 and PC2) explained 100% of the variance (Table 4). For PC1, the variables that showed the highest weight with positive coefficients were Clay, pH, P, Mg and V%. On the other hand, the variables that had highest weight with negative coefficients were Silt, H + Al, TOC and CEC (Table 4). Thus, areas with higher contents of Clay, P and Mg, but which also showed lower values of CEC and TOC, had the score positioned more to the right relative to the origin of PC1 in the biplot graph (Figure 9).

For PC2, the eigenvalues with the highest positive coefficients were associated with the attributes WDC, K, Ca, Na, SB and ESP, while the highest negative eigenvalues were associated with the attributes Sand and DF (Table 4). The calculation of PC1 and PC2 scores in relation to the collection position allowed differentiating the three soil sampling zones – Upper, Midd and Lower (Figure 9). The Upper zone was characterized by a higher amount of exchangeable cations, water-dispersible clay and a lower amount of sand. The Midd position was characterized by the higher sand content and higher potential acidity, while the Lower position was characterized by the higher amount of clay, lower acidity and higher P content (Figure 9). Of these results, the ones that confirm what was found with geostatistics are the higher content of water-dispersible clay in the Upper zone, the higher potential acidity in the Midd zone and the higher clay content in the Lower zone.

In the canonical discriminant analysis, the total variance of the data is explained by the first two variables (CAN1 and CAN2), with 79.15% of the variation contained in CAN1 and 20.85% in CAN2 (Table 5). CAN1, or Fischer's discriminant function, can be represented by [CAN1 = - 110.25HAl + 272.57K + 292.86Ca + 294.70Mg + 294.18Na - 404.83SB + 110.75CEC], indicating that the greater variability found between the studied positions (Upper, Midd and Lower) is explained by the chemical attributes of the soil.

Figure 8 - Spatial distribution of the values of base saturation (V%), cation exchange capacity (CEC - $cmol_c\ dm^{-3}$), phosphorus (P - $mg\ kg^{-1}$) and total organic carbon (TOC - $g\ kg^{-1}$) of the soil collected between terrace channels, in the 0.0 to 0.10 m and 0.10 to 0.20 m layers

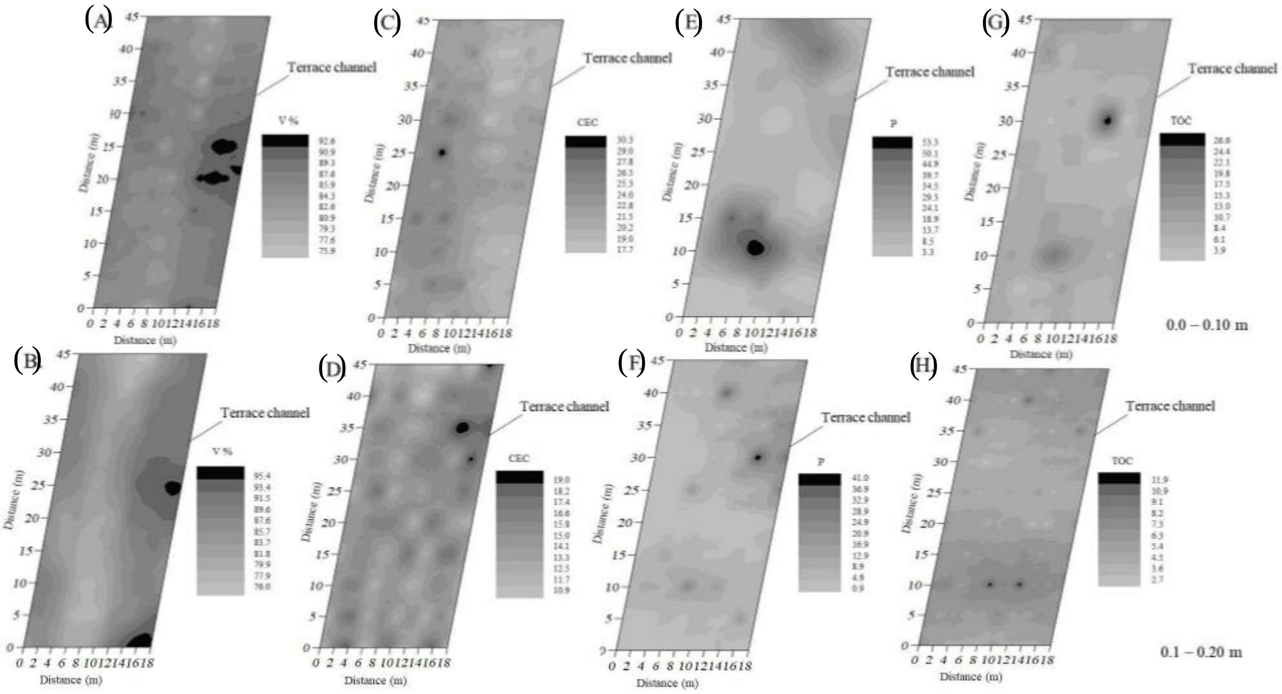


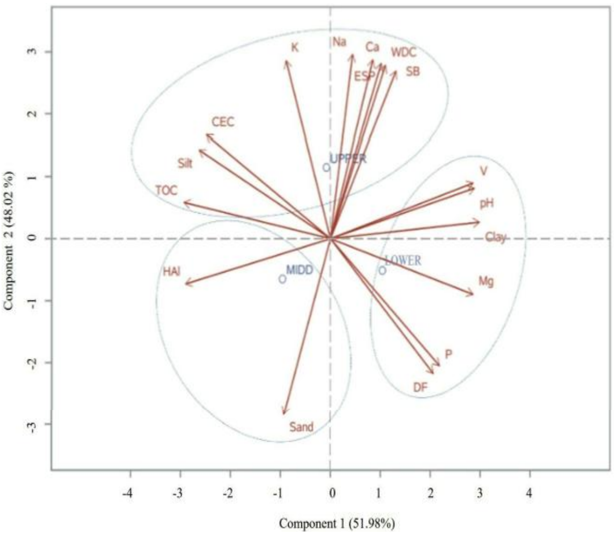
Table 3 - Multivariate analysis of variance (MANOVA) for the physical and chemical attributes of the 0.0 – 0.20 m soil layer in different zones between terrace channels

Variation source	Statistic test	Value	F Value	Pr > F
Zone between terrace channels	Wilks' Lambda	0.10	9.31	< 0.00
	Pillai's Trace	1.32	8.19	< 0.00
	Hotelling-Lawley	5.12	10.55	< 0.00
	Roy's Greatest Root	4.05	17.15	< 0.00

Table 4 - Weight coefficients (eigenvectors), eigenvalues and variance explained by each principal component (PC1 and PC2) for the physical and chemical attributes of the soil studied

Attributes	PC1	PC2
Sand (Sand)	-0.10	-0.33
Silt (Silt)	-0.30	0.17
Clay (Clay)	0.34	0.03
Water-dispersible clay (WDC)	0.12	0.33
Degree of flocculation (DF)	0.23	-0.25
Hydrogen potential (pH)	0.32	0.10
Potential acidity (H+Al)	-0.33	-0.09
Total organic carbon (TOC)	-0.33	0.07
Phosphorus (P)	0.25	-0.24
Potassium (K)	-0.10	0.33
Calcium (Ca)	0.10	0.34
Magnesium (Mg)	0.32	-0.11
Sodium (Na)	0.05	0.35
Sum of bases (SB)	0.15	0.31
Cation exchange capacity (CEC)	-0.28	0.20
Exchangeable sodium percentage (ESP)	0.11	0.33
Base saturation (V%)	0.32	0.10
Eigenvalue	8.84	8.16
Explained variance (%)	51.98	48.02
Cumulative variance (%)	51.98	100.00

Figure 9 - Biplot with the relationship between physical and chemical attributes of the soil and three zones between terrace channels (Upper, Midd and Lower) for the first two principal components (PC1 and PC2). WDC = Water-dispersible clay; DF = Degree of flocculation; HAl = Potential acidity; TOC = Total organic carbon; SB = Sum of bases; CEC = Cation exchange capacity; ESP = Exchangeable sodium percentage



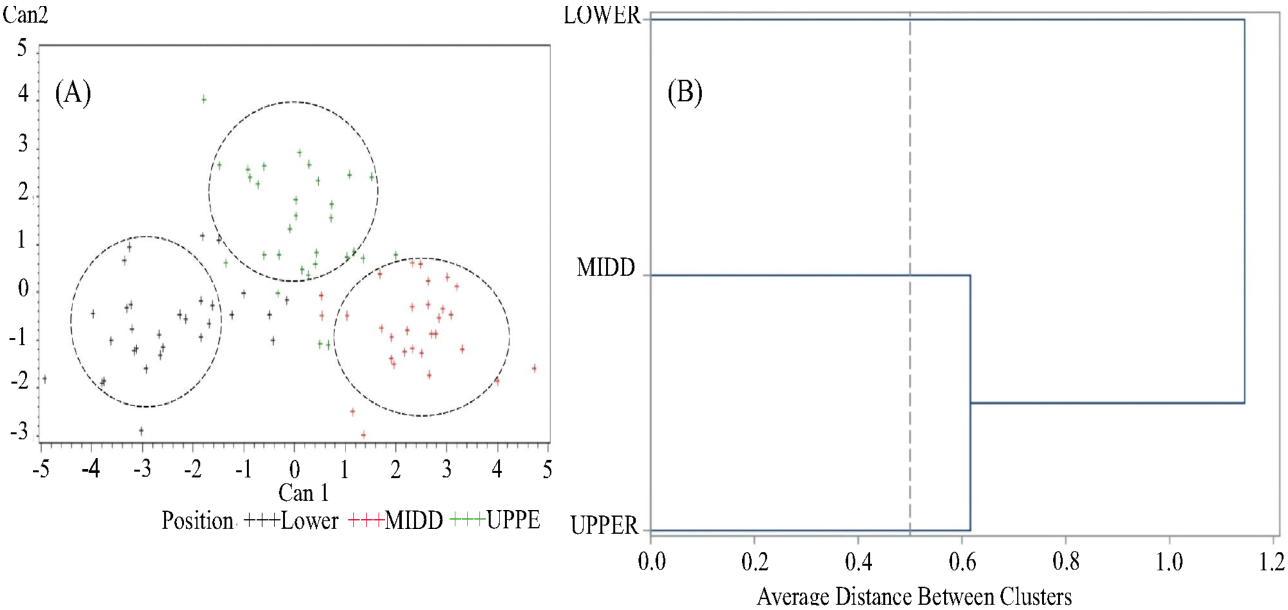
In the joint analysis of the soil attributes, it was found that the Lower and Midd zones were farther apart, while the Upper zone was intermediate, being closer to the Midd (Figure 10A). The dendrogram of the cluster analysis shows the similarity between the positions and, with a cutoff at the Euclidean distance of 0.50, it was possible to identify the formation of three clusters. The first two clusters consisted of the Upper and Midd positions with less similarity between them, while the third cluster consisted of the Lower position (Figure 10B).

When analyzing the means of the soil attributes in each zone evaluated, it was found that the Lower position had higher values of clay content (10 ± 0.7%), degree of flocculation (53.3 ± 3.0%) and base saturation (89.8 ± 0.8%) when compared to the Upper and Midd zones (Table 6). The Upper and Midd zones had higher silt content (21.0 ± 0.9 and 20.8 ± 0.5%, respectively) compared to the Lower zone (18 ± 1.2%) and the Upper zone stood out with higher WDC (5.4 ± 0.4%) when compared to the Midd (3.7 ± 0.2%) and Lower (4.5 ± 0.4%) positions (Table 6). These results are consistent with the graphs of the geostatistical analysis (Figures 4, 6 and 8).

Table 5 - Raw canonical coefficients and total variation explained by each canonical variable (CAN1 and CAN2) for soil physical and chemical attributes

Soil attributes	Position		
	Upper	Midd	Low
Sand (%)	70.6 ± 1.1	72.6 ± 0.6	72.0 ± 1.5
Silt (%)	21.0 ± 0.9	20.8 ± 0.5	18.0 ± 1.2
Clay (%)	8.4 ± 0.3	6.6 ± 0.4	10.0 ± 0.7
WDC(1) (%)	5.4 ± 0.4	3.7 ± 0.2	4.5 ± 0.4
DF(2) (%)	35.1 ± 3.2	41.5 ± 3.9	53.3 ± 3.0
pH	6.3 ± 0.1	6.3 ± 0.1	6.3 ± 0.0
H + Al(3) ($cmol_c\ dm^{-3}$)	2.7 ± 0.2	3.8 ± 0.2	2.1 ± 0.2
TOC(4) ($g\ kg^{-1}$)	7.4 ± 0.5	8.0 ± 0.9	7.0 ± 0.5
P(5) ($mg\ kg^{-1}$)	8.0 ± 1.9	14.2 ± 3.8	12.8 ± 3.0
K ($cmol_c\ dm^{-3}$)	0.3 ± 0.0	0.3 ± 0.0	0.3 ± 0.0
Ca ($cmol_c\ dm^{-3}$)	15.5 ± 0.7	14.0 ± 0.6	14.7 ± 0.6
Mg ($cmol_c\ dm^{-3}$)	2.7 ± 0.2	2.6 ± 0.1	3.0 ± 0.1
Na ($cmol_c\ dm^{-3}$)	0.5 ± 0.0	0.4 ± 0.0	0.4 ± 0.0
SB(6) ($cmol_c\ dm^{-3}$)	18.9 ± 0.8	17.4 ± 0.6	18.4 ± 0.6
CEC(7) ($cmol_c\ dm^{-3}$)	21.6 ± 0.8	21.2 ± 0.7	20.5 ± 0.6
ESP(8) (%)	2.3 ± 0.1	2.1 ± 0.1	2.2 ± 0.1
V(9) (%)	87.5 ± 0.9	81.5 ± 1.1	89.8 ± 0.8

Figure 10 - Dispersion of the physical and chemical attributes of the soil in the Upper, Midd and Lower zones between terrace channels according to canonical variables 1 and 2 (A) and dendrogram of the hierarchical cluster analysis for the positions studied (B)



Water-dispersible clay is being transported from the Upper zone to the Lower zones, indicating that it is a loss zone (Amare *et al.*, 2013). Following the line of reasoning that the Upper position is one of loss, it was expected to have a higher sand content, because in the laminar erosion process there is selectivity of particles

Table 6 - Means (± standard deviation) of the physical and chemical attributes in the 0.0 to 0.20 m layer of soil collected at the Upper, Midd and Lower positions between terrace channels of the studied area

Soil attributes	Position		
	Upper	Midd	Low
Sand (%)	70.6 ± 1.1	72.6 ± 0.6	72.0 ± 1.5
Silt (%)	21.0 ± 0.9	20.8 ± 0.5	18.0 ± 1.2
Clay (%)	8.4 ± 0.3	6.6 ± 0.4	10.0 ± 0.7
WDC(1) (%)	5.4 ± 0.4	3.7 ± 0.2	4.5 ± 0.4
DF(2) (%)	35.1 ± 3.2	41.5 ± 3.9	53.3 ± 3.0
pH	6.3 ± 0.1	6.3 ± 0.1	6.3 ± 0.0
H + Al(3) ($cmol_c$ dm^{-3})	2.7 ± 0.2	3.8 ± 0.2	2.1 ± 0.2
TOC(4) (g kg^{-1})	7.4 ± 0.5	8.0 ± 0.9	7.0 ± 0.5
P(5) (mg kg^{-1})	8.0 ± 1.9	14.2 ± 3.8	12.8 ± 3.0
K ($cmol_c$ dm^{-3})	0.3 ± 0.0	0.3 ± 0.0	0.3 ± 0.0
Ca ($cmol_c$ dm^{-3})	15.5 ± 0.7	14.0 ± 0.6	14.7 ± 0.6
Mg ($cmol_c$ dm^{-3})	2.7 ± 0.2	2.6 ± 0.1	3.0 ± 0.1
Na ($cmol_c$ dm^{-3})	0.5 ± 0.0	0.4 ± 0.0	0.4 ± 0.0
SB(6) (cmolc dm-3)	18.9 ± 0.8	17.4 ± 0.6	18.4 ± 0.6
CEC(7) ($cmol_c$ dm^{-3})	21.6 ± 0.8	21.2 ± 0.7	20.5 ± 0.6
ESP(8) (%)	2.3 ± 0.1	2.1 ± 0.1	2.2 ± 0.1
V(9) (%)	87.5 ± 0.9	81.5 ± 1.1	89.8 ± 0.8

(1) WDC = Water-dispersible clay; (2) DF = Degree of flocculation; (3) H+Al = Potential acidity; (4) TOC = Total organic carbon; (5) P = Available phosphorus (Mehlich-1 extractant); (6) SB = Sum of bases; (7) CEC = Cation exchange capacity; (8) ESP = Exchangeable sodium percentage; (9) V = Base saturation

to be removed, so that the finer ones are transported and the coarser ones are concentrated on the surface (Hewawasam; Illangasinghe, 2015). However, the Upper position did not show more sand than the Midd and Lower positions (Table 6). On the other hand, when evaluating the Midd and Lower positions, the former had higher sand content than the latter (Table 6).

With regard to available P (Table 6), the highest content (14.2 ± 3.9 mg kg^{-1}) was observed in the Midd position, followed by the Lower (12.8 ± 3.0 mg kg^{-1}) and Upper (8 ± 1.9 mg kg^{-1}) positions, which is consistent with the geostatistical analysis (Figure 8E, 8F). In a study in which the available P contents in the soil were compared in different positions relative to the terrace channels, the lowest content was observed in the Upper position, followed by the Midd and Lower positions, which in turn did not differ from each other (Wolka *et al*., 2022). Thus, the possibility that the differences in P contents are due to erosive processes whose effects have been more pronounced from the Upper position to the Midd position and less pronounced from the Midd position to the Lower position is not ruled out. As the Upper position is 12 to 18 meters above the terrace channel, this range is the one requiring greatest attention regarding the need for replacement of organic matter and nutrients.

Cluster analysis indicated coherence with the observations found in the principal component and canonical analyses. Multivariate analysis allowed the identification of the same effects observed by geostatistics for clay content, water-dispersible clay and potential acidity. In addition, the multivariate analysis made it possible to identify differences in the sum of bases, sand content and phosphorus content that were not observed in the geostatistical analysis. The importance of using geostatistics to identify the variability of soil attributes in terraced areas is clear, highlighting that the multivariate approach is considered a trend for future studies (Silva; Manzione; Oliveira, 2023). The variability of soil attributes in the different positions between terraces was identified, reinforcing the importance of techniques for diagnosis and prediction of soil management strategies.

CONCLUSIONS

1. Geostatistical and multivariate analysis approaches showed differences in the physical and chemical attributes of the soil in different positions between terraces under the edaphoclimatic conditions of the Brazilian semi-arid region;

2. The upper position, which is in the range of 12 to 18 meters above the terrace channel, presents itself as a loss zone, requiring a greater supply of organic matter and phosphorus, as well as care measures that favor the aggregation and stability of soil aggregates. The intermediate and low positions present themselves as deposition zones, and the intermediate position has more favorable aspects regarding higher phosphorus content, when compared to the low position;

3. This study was the first step in assessing the effects of terracing on soil quality in a semi-arid region of Brazil. The observations found with the use of geostatistical and multivariate analysis tools contributed to the knowledge of soil attributes in terraced areas, which can be used by technicians and farmers as premises for land use planning.

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