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ENVIRONMENTAL FRAGILITY PROVIDED BY SOILS OF A PLATEAU EDGE OF SOUTH BRAZIL, ON ATLANTIC FOREST BIOME

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ABSTRACT

Plateau areas have been considered with high land-use capacity in the Brazilian Meridional Plateau Edge of South Brazil. These areas belong to Atlantic Forest biome, the second most extinction threatened ecoregion in the world. The weak knowledge about this environment leads to intensive use and degradation. We aimed to identify soil fragility and land-use capacity and limitation of the Brazilian Meridional Plateau Edge, in South Brazil, by verifying the soil properties. Soil morphology, steady-state water infiltration, and physical and chemical properties at 0.00-0.10 and 0.10-0.20 m layers were evaluated at 57 sampling points (2 ha) in a grid of 20 x 20 m. Although under a small slope, these areas have high soils variability, which implies high natural fragility. Unlike the soils and its properties expected due to the local soil-landscape relationship, naturally fragile soils (Leptosols, Regosols) with only patches of developed soils (Cambisols, Alisols, Planosols/Gleysols) predominate in these areas. These soils have been intensively degraded because the land-use capacity indicator is, mainly, the low altimetric amplitude. However, proper use and management depend on planning based on the spatial distribution of soil properties and on the fragility of soils.

Keywords: Low altimetric amplitude. Land-use capacity. Soils variability. Shallow soils. Intensive land-use.

FRAGILIDADE AMBIENTAL PROPORCIONADA POR SOLOS DO REBORDO DO PLANALTO MERIDIONAL DO SUL DO BRASIL, NO BIOMA MATA ATLÂNTICA

RESUMO

Áreas de patamar têm sido consideradas com alta capacidade de uso no Rebordo do Planalto Meridional do sul do Brasil. Essas áreas pertencem ao bioma Mata Atlântica, segunda ecorregião mais ameaçada de extinção do mundo. O conhecimento incipiente desse ambiente leva à intensivos usos e degradação. Objetivamos identificar a fragilidade do solo e o potencial de uso das terras do Rebordo do Planalto Meridional do sul do Brasil, por meio de propriedades dos solos. A morfologia, a infiltração de água e as propriedades físicas e químicas do solo, nas camadas de 0,00-0,10 e 0,10-0,20 m, foram avaliadas em 57 pontos (2 ha) em uma malha de amostragem de 20 x 20 m. As áreas de patamar, embora com pouca declividade, possuem alta variabilidade de solos, o que implica em alta fragilidade natural. Diferentemente dos solos e suas propriedades esperadas devido a relação solo-paisagem local, solos naturalmente frágeis (Neossolos Litólicos, Neossolos Regolíticos) predominam nessas áreas, com apenas núcleos de solos desenvolvidos (Cambissolos, Argissolos, Planossolos/Gleissolos). Esses solos vem sendo intensamente degradados por terem seu potencial de uso baseado, principalmente, na baixa amplitude altimétrica. Contudo, o uso e manejo adequado depende do planejamento baseado distribuição espacial das propriedades e na fragilidade dos solos.

Palavras-chave: Baixa amplitude altimétrica. Capacidade de uso das terras. Variabilidade do solo. Solos rasos. Uso intensivo do solo.

INTRODUCTION

The Atlantic Forest biome is the second most extinction threatened ecoregion in the world. This biome extends along the Brazilian Atlantic coast (1,110,182 km^2; 15% of Brazilian territory), and part of Paraguay and Argentina, with an original total area of 1,500,000 km^2 in South America. Over 85% of the Atlantic Forest original area has been deforested. The biome has 97,596 km^2 (7.26% of the original area, approximately) of well-preserved forest remnants, in Brazil (RIO GRANDE DO SUL, 2009). In the southernmost Brazilian state of Rio Grande do Sul (RS), only 7.5% of the Atlantic Forest remains, with a high fragmentation degree in relation to the original vegetation cover (RIO GRANDE DO SUL, 2019).

The Brazilian Meridional Plateau Edge of the Rio Grande do Sul state (RS) has remnants of the Atlantic Forest biome, characterized by the Subtropical Seasonal Forest. These forest remnants have high vegetation diversity and compose part of the largest and most important ecological connection areas among native forests in South Brazil (MARCUZZO; PAGEL; CHIAPPETTI, 1998; SCIPIONI et al., 2010; 2012). Despite of their environmental importance, the Atlantic Forest areas have been degraded due to the replacement of native vegetation by agricultural and livestock production (IZQUIERDO; DE ANGELO; AIDE, 2008; TABARELLI et al., 2010). Furthermore, the agricultural land-use is performed without the land-use capacity evaluation, where the soil capacity is frequently misunderstood.

The occurrence of the hilly relief, composed by hills, cliffs and steep slopes covered by dense forests, interconnected by plateau with flat up to smooth undulating relief is a common feature of the Brazilian Meridional Plateau Edge of the RS (ROBAINA; CRISTO; TRENTIN, 2011). Shallow soils, mainly Leptosols, fragile to anthropic use and considered unfit for agriculture predominate in the sloping areas of this environment (PEDRON and DALMOLIN, 2011; LEPSCH et al., 2015). Nevertheless, these soils have been gradually degraded due to the agriculture intensive use.

The areas under low slope relief (flat to smooth undulating relief) of the plateau, on the other hand, are homogeneous, with more developed and deeper soils such as Cambisols, Nitisols, Alisols and Umbrisols, according to non-detailed soil surveys performed in the region (PEDRON and DALMOLIN, 2011). This relief condition favors the soil development (WOLSKI et al., 2017) due to the increase in water infiltration and percolation through the soil profile (NICÓTINA et al., 2011; PETERMAN et al., 2014). Although, field observations have indicated different behavior of soil development in the areas under low slope relief of the plateau.

Generally, areas with steep relief have high pedological variability (TERAMOTO; LEPSCH; VIDAL-TORRADO, 2001; DALMOLIN et al., 2004), with high complexity of soil class distribution (DALMOLIN et al., 2004), while relief areas under low slope (plateau/high plain/tableland) favor lower variability of chemical, physical and morphological properties of soils due to geomorphological stability (TERAMOTO; LEPSCH; VIDAL-TORRADO, 2001), due to the soil-landscape relationship (CEDDIA et al., 2009). However, the typical geomorphological variability of the Brazilian Meridional Plateau Edge conditioners a greater soil variability, which makes these environments fragile naturally. These soil occurrence and variability are unknown, which favors the environmental fragility increase due to the agricultural use above the soil capacity.

The lack of knowledge about soil classes and properties in these areas have leading farmers to perform indiscriminate land-use for agriculture and livestock in areas suitable only for forestry and natural preservation (PEDRON et al., 2006). The low relief slope of the plateau favors the intensive land-use of these areas, which increase soil degradation processes such as erosion, water stress, and roots development restrictions (PEDRON and DALMOLIN, 2011).

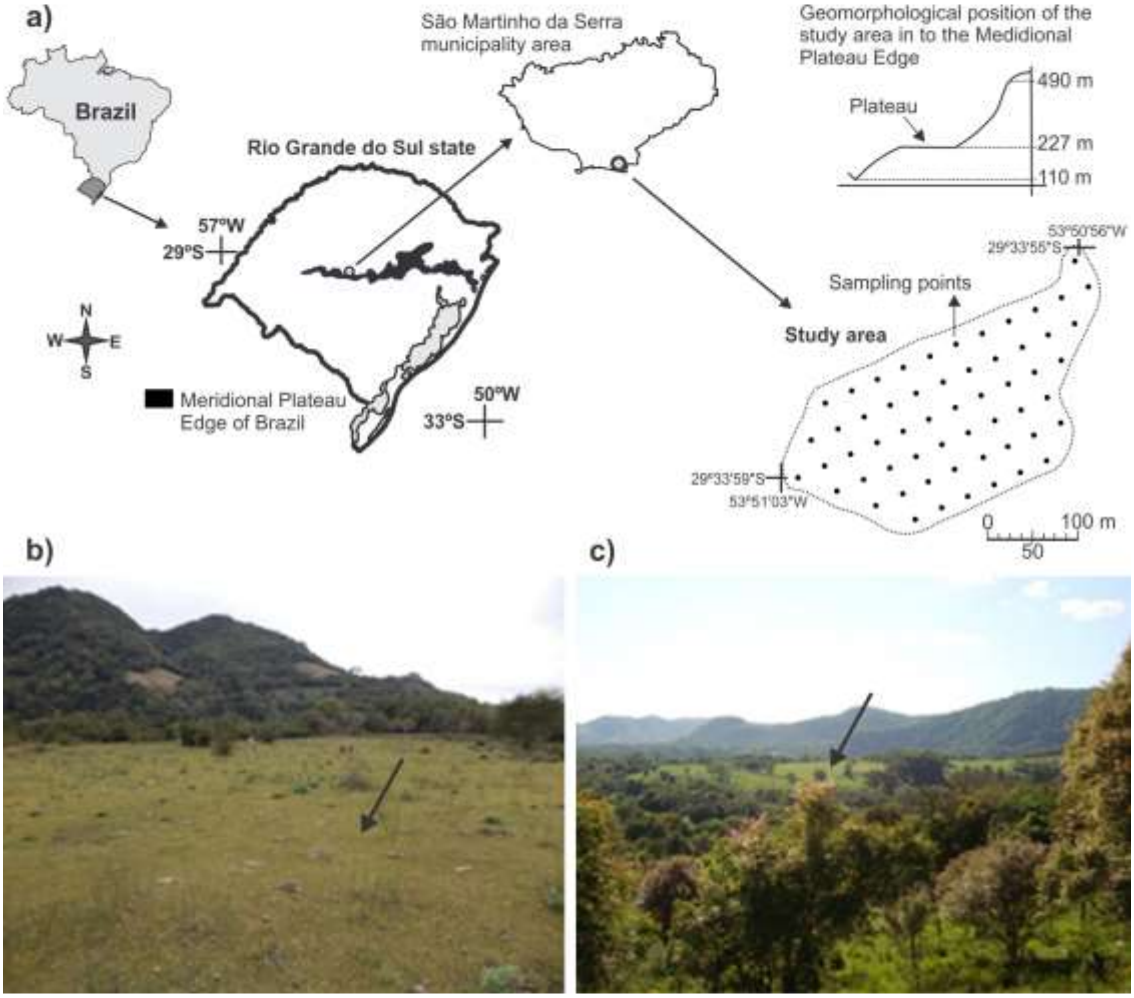
The absence of prior analysis of the land-use capacity and of the environmental fragility of soil classes and its properties, prior to the incorporation of areas covered by forest or native grassland into the agricultural and livestock systems, have been the main reason for degradation. The intensive occupation of the plateau for agriculture has been providing soil degradation due to the low capacity for land-use and inadequate agricultural management. Soil is the support for vegetation growth, development, and establishment. The knowledge about soil distribution and its properties is necessary to evaluate the land-use capacity for the management and sustainability of Atlantic Forest biome. For this reason, we aimed to identify the soils occurrence pattern, the variability existence of the soil physical properties within the same class and their behavior and, to identify the physical, chemical and morphological properties that best describe soil classes, in order to understand the potentials and land-use limitations of the Brazilian Meridional Plateau Edge of the RS state, in South Brazil.

MATERIAL AND METHODS

Study sites

The study was performed in a natural grassland area (2 ha), located in the São Martinho da Serra municipality, in RS , southern Brazil (Figure 1a). The area is characterized by average elevation of 227 m, in the middle third of the Brazilian Meridional Plateau Edge, under a flat to smooth undulating relief, in a plateau area (Figure 1b) situated between cliffs and steep slopes (Figure 1c).

Figure 1 - Rio Grande do Sul State, South Brazil: Location of study area and sampling points (a), with steep slopes areas used for agriculture (b) and plateau, in flat up to smooth undulating relief (b, c), in the Meridional Plateau Edge. The arrows in the b and c images indicate the study area.



Climate is humid subtropical (Cfa), with no dry season (ÁLVARES et al., 2013), according classification of Köppen. Average annual temperature is 19.2 °C, and average annual rainfall is 1,708 mm (MALUF, 2000; ÁLVARES et al., 2013).

The geology is composed of basic volcanic rocks from the Serra Geral Formation, with a surrounding contribution of intertrapic sandstone of the Botucatu Formation (SARTORI, 2009). Ferralsols (*Latossolos*), Nitisols (*Nitossolos*), Alisols and Umbrisols (*Argissolos*), and Leptosols (*Neossolos*) predominate in these areas, according to Streck et al. (2018).

The original forest vegetation in the region of study area belongs to seasonal semideciduous forest (*Floresta Estacional Semidecidual*; IBGE, 2012). The vegetation was composed mainly of *Soliva pterosperma* (Juss.) Less*.*, *Desmodium tortuosum* (Sw.) DC.*, Baccharis trimera* (*Less.) DC*. and grasses of the genus *Paspalum* ssp. and, under lower occurrence of *Commelina longicaulis* Jacq*.*, *Senegalia bonariensis* (Gillies ex Hook. & Arn.) Seigler & Ebinger and *Eugenia uniflora* L. (SCIPIONI et al., 2010; KILCA et al., 2015).

The study area is a 2 ha pasture and crop field surrounded by natural forest. It belongs to a private property and was maintained for at least 10 years with natural pasture for livestock production until 2013, when this study begun. Subsequently, the area was inserted into agricultural system production and cropped with soybean (*Glycine max* (L.) Merr.) during the summer and with black oat (*Avena strigosa* Schieb) during the winter.

Soil evaluation and sampling

Soil evaluations were performed at 57 sampling points in a grid of 20 x 20 m. At each point, soil pits were excavated and a profile has been cleaned and prepared for describing the soil morphology (SANTOS et al., 2015). Soil profiles had enough depth to expose B horizon and/or R layer. The morphological soil properties evaluated were A horizon thickness (AHT), lithic contact depth (LCD) and saprolitic layer thickness (SLT). These information were used to produce the soil map of the area.

Soil sampling to evaluate soil physical and chemical properties and analysis of steady-state water infiltration were performed at the same points of morphological description. Disturbed soil samples were taken from layers 0.00-0.10 and 0.10-0.20 m to determine particle size distribution and chemical properties. Undisturbed soil samples were collected in 0.05 m diameter and 0.03 m height metal rings from the above mentioned layers to determine soil bulk density (BD), total porosity (TP), macroporosity (Mac), microporosity (Mic), and saturated hydraulic conductivity (Ks). These soil layers were selected considering their importance to the plant roots development and the shallow depths of the predominant soils in the area.

Steady-state water infiltration (ic) was determined by one measurement at each sampling point by the method of concentric ring infiltrometer (BERNARDO et al., 2019), which consists of inserting two concentric cylinders with different diameters into the soil surface, an arrangement that delimits two compartments that were filled with water. The amount of water infiltrating into the inner cylinder was determined by readings at 1, 5, 10, 15, 20, 30, 45, 60, 90, 120, 150 and 180 minutes after the test beginning.

Disturbed soil samples were air-dried, 2-mm sieved, and used to analyze particle size distribution (DONAGEMMA et al., 2017) with dispersion procedure described by Suzuki et al. (2015), and quantification followed the pipette method (GEE and BAUDER, 1986).

The undisturbed soil samples were capillary-saturated for 24 h, and then subjected to 6 kPa water tension in a sand column (REINERT and REICHERT, 2006). Subsequently, soil samples were capillary-saturated for 24 h, and saturated hydraulic conductivity was measured with a constant-head permeameter (KLUTE, 1986). Finally, the samples were dried in an oven at 105 °C until reaching constant weight to quantify soil bulk density (BLAKE and HARTGE, 1986).

Total porosity corresponds to the soil water content at saturation, microporosity was calculated based on water retention at 6 kPa, and macroporosity is the difference between total porosity and microporosity (DANIELSON and SUTHERLAND, 1986).

Disturbed soil samples were also used to determine chemical properties, in order to classify the soils and to identify the properties that best describe soil classes. Properties evaluated were soil pH in water, soil exchangeable bases (K, Na, Ca and Mg) and aluminum contents, and soil organic carbon (OC). Soil pH in water (1:2.5 v/v; pH_H_2O) was evaluated with procedure described by Teixeira; Campos; Saldanha (2017). Soil available K (potassium) and Na (sodium) were extracted with Mehlich-I solution (0.05 mol L^{-1} HCl + 0.0125 mol L^{-1} H_2SO_4) and measured by flame photometry; and Ca (calcium), Mg (magnesium) and Al (aluminum) were extracted by 1 mol L^{-1} KCl, where Ca and Mg were measured with an atomic absorption, while Al was measured by titration with 0.0125 mol L^{-1} NaOH solution (TEDESCO et al., 1995). Sum of bases (S = Ca + Mg + K + Na), effective (CECe = Al + Ca + Mg + K + Na) and at pH 7.0 (CECpH7 = H + Al + Ca + Mg + K + Na) cation exchange capacity, bases saturation (V = (SB/CECpH7) x 100), and aluminum saturation (m = (Al/ CECe) x 100) were calculated. Soil organic carbon (OC) was analyzed by wet combustion method (NELSON and SOMMERS, 1982).

Soil analysis

Descriptive statistical analysis was performed in order to obtain minimum, mean, maximum, asymmetry, variance and kurtosis values of physical, chemical and morphological properties obtained at the sampling points. Data normality was assessed by the Kolmogorov-Smirnov ($d < 0.05$ = non-normal distribution; $d > 0.05$ = normal distribution). The coefficient of variation (CV) were classified as low variability (CV < 12%), mean variability ($12 \leq CV \leq 62\%$) and high variability (CV > 62%), according to Warrick and Nielsen (1980).

Subsequently, due to the soil properties variability, two strategies were considered for the data analysis, in order to sustainable land-use planning, according to the soil properties that best describe the soil classes:

(i) The soils at each sampling point were classified according to the Brazilian Soil Classification System (SANTOS et al., 2018) and according to the World Reference Base for Soil Resources (IUSS WORKING GROUP WRB, 2015). The variability of soil classes and properties within each soil class was represented in maps, when properties had spatial dependence. The spatial dependence of soil classes and properties was evaluated by semivariograms, considering the Akaike's Information Criterion (AKAIKE, 1983), the smallest mean square error, the highest coefficient of determination and the lowest root mean square error, and based on the intrinsic hypothesis principles (GOOVAERTS, 1997). The soil classes and properties values of each point were interpolated by the kriging method for mapping soil, when data had spatial dependence.

(ii) Principal component analysis (PCA) was performed in each soil layer in order to evaluate the properties that best characterize each soil class. The PCA uses a vector space transform to reduce the dimensionality of large data sets. The soil properties vectors in the same direction and sense are positively correlated while vectors in opposite directions are negatively correlated. Vectors with angles close to 90 degrees are independent, had no relationship. Individuals (soils) that are in the direction of the vectors are associated with them. These statistical analyses were performed in the R environment (R CORE TEAM, 2019).

RESULTS

Soil properties variability

Most physical, chemical and morphological soil properties had mean ($12 \leq CV \leq 62\%$) or high (CV > 62%) variability at the surface (0.00-0.10 m) and the subsurface (0.10- 0.20 m) soil layers, considering all sampling points, even that study area is small (2 ha) and the elevation had low altimetric amplitude (mean elevation = 227.54 m; CV = 0.64%) (Table 1).

Table 1 - Elevation and morphological, physical and chemical soil properties of the study area.

Property	Minimum	Maximum	Mean	Variance	Asymmetry	Kurtosis	CV%	D
Elevation (m)	223.92	231.26	227.54	2.12	0.39	0.59	0.64	0.64
ic (mm h^{-1})	4.14	538.58	76.49	7328.33	3.38	15.09	111.91	0.02^{ns}
AHT (m)	0.04	0.50	0.16	0.01	1.00	1.92	56.25	0.55
SLT (m)	0.00	0.70	0.28	0.05	0.36	-1.29	83.14	0.16
LCD (m)	0.05	1.70	0.61	0.16	1.17	1.36	64.87	0.32
0.00-0.10 m								
Ks (mm h^{-1})	38.48	690.85	226.70	32541.69	1.24	0.59	79.57	0.02^{ns}
BD (Mg m^{-3})	0.99	1.59	1.18	0.01	0.98	3.62	8.64	0.57
TP (m^{3} m^{-3})	0.55	0.68	0.61	0.00	0.10	-0.19	4.80	0.74
Mac (m^{3} m^{-3})	0.10	0.27	0.17	0.00	0.48	-0.69	24.45	0.46
Mic (m^{3} m^{-3})	0.35	0.52	0.43	0.00	0.01	0.48	7.71	0.57
Clay (g kg^{-1})	167.75	363.99	237.69	1379.13	0.55	1.05	15.62	0.95
Sand (g kg^{-1})	272.57	524.96	437.98	2139.19	-0.60	1.65	10.56	0.99
Silt (g kg^{-1})	239.13	449.45	324.34	1270.72	0.22	1.92	10.99	0.77
Mgravel (%)	0.00	49.89	14.63	273.83	0.66	-1.10	113.12	0.00^{ns}
Fgravel (%)	1.36	48.99	18.85	116.00	0.54	-0.07	57.15	0.65
ADFE (%)	25.70	97.52	66.53	497.65	-0.27	-1.35	33.53	0.36
OC (%)	2.06	4.29	3.04	0.31	0.48	-0.37	18.47	0.53
0.10-0.20 m								
Ks (mm h^{-1})	28.29	1087.58	204.89	37801.83	2.68	9.15	94.89	0.08
BD (Mg m^{-3})	0.98	1.42	1.23	0.01	-0.15	1.00	6.64	0.96
TP (m^{3} m^{-3})	0.50	0.73	0.58	0.00	1.73	5.11	7.09	0.05^{ns}
Mac (m^{3} m^{-3})	0.12	0.32	0.18	0.00	1.17	1.92	21.94	0.71
Mic (m^{3} m^{-3})	0.33	0.45	0.40	0.00	-0.44	1.20	5.61	0.75
Clay (g kg^{-1})	183.52	376.42	263.14	1552.37	0.39	0.23	14.97	0.97
Sand (g kg^{-1})	302.75	491.56	401.45	1513.28	-0.09	-0.05	9.69	0.90
Silt (g kg^{-1})	240.63	411.32	335.41	1065.22	-0.34	0.35	9.73	0.94
Mgravel (%)	0.00	61.82	18.59	352.87	0.61	-0.67	101.02	0.01^{ns}
Fgravel (%)	0.27	59.66	24.53	210.92	0.47	-0.43	59.21	0.93
ADFE (%)	16.27	99.73	56.87	676.60	0.23	-1.43	45.73	0.42
OC (%)	1.71	4.06	2.56	0.30	0.92	0.36	21.21	0.07

CV - coefficient of variation; d: Kolmogorov-Smirnov test significance; ns: no significant differences; ic: steady-state water infiltration; AHT: A horizon thickness; SLT: saprolitic layer thickness; LCD: lithic contact depth; Ks: soil saturated hydraulic conductivity; BD: soil bulk density; TP: total porosity; Mac: macroporosity; Mic: microporosity; Mgravel: medium gravel (200.00-20.00 mm); Fgravel: fine gravel (20.00-2.00 mm); ADFE: air-dried fine earth fraction (< 2.00 mm); OC: soil organic carbon.

Steady-state water infiltration (from 4.14 up to 538.58 mm h^{-1}), saprolitic layer thickness (from 0.00 up to 0.70 m) and lithic contact depth (from 0.05 up to 1.70 m) had high variability (CV > 62%), while A horizon thickness (from 0.04 up to 0.50 m) had mean variability (Table 1).

The Ks and the medium gravel had high variability at the 0.00-0.10 m and 0.10-0.20 m soil layers. The Ks and fine gravel ranged from 38.48 up to 690.85 mm h^{-1} and from 0.00 up to 49.89% at the 0.00-0.10 m soil layer, respectively, and from 28.29 up to 1087.58 mm h^{-1} and from 0.00 up to 61.82% at the 0.10-0.20 m soil layer, respectively (Table 1).

Macroporosity, clay and soil organic carbon content had average variability at the 0.00-0.10 m and 0.10-0.20 m soil layers. At the surface layer (0.00-0.10 m), macroporosity ranged from 0.10 up to 0.27 $m^3 m^{-3}$, clay content ranged from 167.75 up to 363.99 g kg^{-1} and soil organic carbon ranged from 2.06 to 4.29%. At the subsurface layer (0.10-0.20 m), macroporosity ranged from 0.12 up to 0.32 $m^3 m^{-3}$, clay content ranged from 183.52 up to 376.42 g kg^{-1} and soil organic carbon ranged from 1.71 up to 4.06% (Table 1).

Soil bulk density, total porosity, microporosity, and sand and silt contents had low variability in the study area at the 0.00-0.10 m and 0.10-0.20 m soil layers (CV < 12%). At the surface layer, soil bulk density ranged from 0.99 up to 1.59 Mg m^{-3}, total porosity from 0.55 up to 0.68 $m^3 m^{-3}$, microporosity from 0.35 up to 0.52 $m^3 m^{-3}$, and sand from 272.57 up to 524.96 g kg^{-1} and silt from 239.13 up to 449.45 g kg^{-1}. At the subsurface layer, soil bulk density ranged from 0.98 up to 1.42 Mg m^{-3}, total porosity from 0.50 up to 0.73 $m^3 m^{-3}$, microporosity 0.33 up to 0.45 $m^3 m^{-3}$, and sand from 302.75 up to 491.56 g kg^{-1} and silt from 240.63 up to 411.32 g kg^{-1} (Table 1).

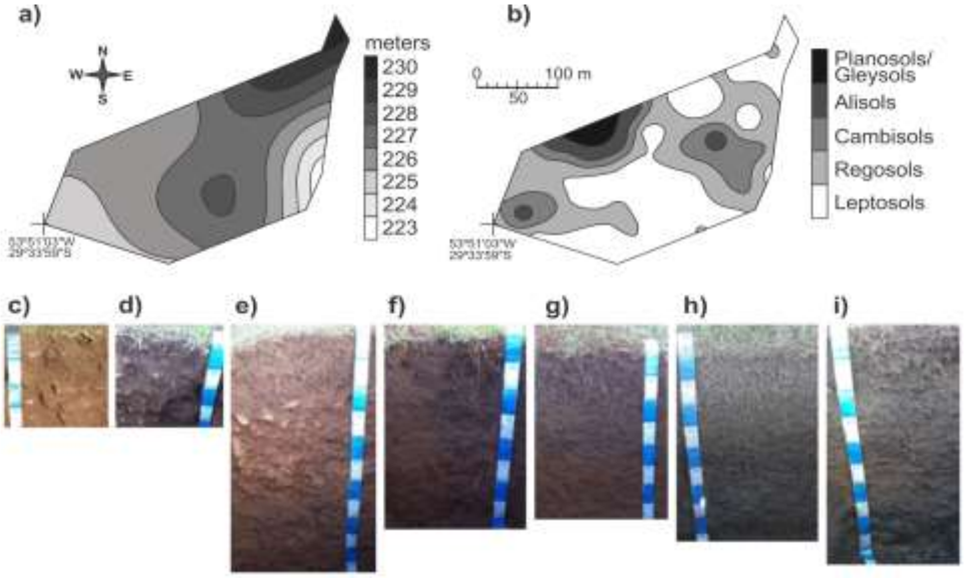
Steady-state water infiltration, saturated hydraulic conductivity and medium gravel at the surface layer (0.00-0.10 m), and total porosity and medium gravel at the subsurface (0.10-0.20 m) layer had non-normal distribution, considering all sampling points in the study area (Table 1).

The highest variances were observed for ic and Ks. Asymmetry and kurtosis indicate that BD at the surface layer and Mac at the subsurface layer are non-symmetric, even though these properties had normal distribution (Table 1).

Occurrence, spatial distribution and physical, chemical and morphological properties of soils

Seven soil classes was obtained by the soil survey, named as: *Neossolo Litólico Eutrófico fragmentário* or Lithic Leptosol, *Neossolo Regolítico Distrófico léptico* or Leptic Regosol, *Cambissolo Háplico Ta Eutrófico típico* or Leptic Cambisol, *Argissolo Bruno-Acinzentado Ta Alumínico abrúptico* or Haplic Alisol, *Argissolo Vermelho Eutrófico abrúptico* or Rhodic Alisol, *Planossolo Háplico Eutrófico vertissólico* or Gleyic Planosol, and *Gleissolo Háplico Ta Eutrófico típico* or Eutric Gleysol (Figure 2), according to the Brazilian Soil Classification System (SANTOS et al., 2018) and the WRB (IUSS WORKING GROUP WRB, 2015), respectively. These soils had high variability of properties between classes.

Figure 2 - Elevation (a) and spatial distribution of soil classes (b) maps, and soil profiles of the study area: *Neossolo Litólico Eutrófico fragmentário* or Lithic Leptosol (c), *Neossolo Regolítico Distrófico léptico* or Leptic Regosol (d), *Cambissolo Háplico Ta Eutrófico típico* or Leptic Cambisol (e), *Argissolo Vermelho Eutrófico abrúptico* or Rhodic Alisol (f), *Argissolo Bruno-Acinzentado Ta Alumínico abrúptico* or Haplic Alisol (g), *Planossolo Háplico Eutrófico vertissólico* or Gleyic Planosol (h) and *Gleissolo Háplico Ta Eutrófico típico* or Eutric Gleysol (i). The White and blue in the metric tape have 10 cm deep.



Soil properties within each class had normal distribution and lower variability compared to the variability of soils taken from all sampling points. Even with this reduction, some properties still had high variability in some soil classes (Table 2; Figures 3 and 4). Elevation had low altimetric amplitude within different soil classes (Table 2), as observed in the entire dataset (Table 1).

Table 2 - Elevation and morphological, physical and chemical soil properties of the soil classes of study area.

Property	Leptosols		Regosols		Cambisols		Alisols	
	Mean	CV%	Mean	CV%	Mean	CV%	Mean	CV%
Elevation (m)	227.87	1	227.63	1	226.71	1	226.88	0
ic (mm h^{-1})	68.48	97	76.97	69	71.44	115	130.58	154
AHT (m)	0.14	60	0.15	44	0.23	75	0.23	18
SLT (m)	0.14	95	0.52	25	0.20	118	0.07	54
LCD (m)	0.28	47	0.67	19	0.69	29	1.33	27
0.00-0.10 m								
Ks (mm h^{-1})	231.57	82	252.38	70	153.51	66	215.93	111
BD (Mg m^{-3})	1.20	10	1.17	8	1.20	7	1.14	5
TP (m^3 m^{-3})	0.61	5	0.61	5	0.62	6	0.60	3
Mac (m^3 m^{-3})	0.18	24	0.18	23	0.16	25	0.14	17
Mic (m^3 m^{-3})	0.42	8	0.42	6	0.46	6	0.46	5
Clay (g kg^{-1})	235.03	15	230.49	16	274.92	19	234.07	8
Sand (g kg^{-1})	435.26	13	442.48	9	424.24	11	452.56	10
Silt (g kg^{-1})	329.71	13	327.04	8	300.85	7	313.37	14
Mgravel (%)	19.33	92	17.28	94	3.33	224	1.60	245
Fgravel (%)	20.87	55	20.24	53	13.97	71	13.42	53
ADFE (%)	59.81	37	62.47	35	82.70	20	84.98	11
OC (%)	3.19	21	2.94	16	2.61	19	3.13	10
0.10-0.20 m								
Ks (mm h^{-1})	224.46	83	240.75	102	164.42	80	120.33	46
BD (Mg m^{-3})	1.22	9	1.25	5	1.23	5	1.22	7
TP (m^3 m^{-3})	0.60	7	0.59	7	0.56	3	0.56	6
Mac (m^3 m^{-3})	0.20	22	0.19	20	0.16	6	0.16	16
Mic (m^3 m^{-3})	0.40	5	0.40	5	0.41	4	0.40	9
Clay (g kg^{-1})	255.39	13	250.97	14	309.40	12	278.68	12
Sand (g kg^{-1})	402.48	9	404.65	9	382.57	11	417.06	11
Silt (g kg^{-1})	342.13	10	344.39	8	308.03	6	304.26	13
Mgravel (%)	26.69	77	19.65	81	5.44	195	1.04	245
Fgravel (%)	25.36	58	27.35	47	22.52	66	18.71	102
ADFE (%)	47.95	53	53.00	42	72.04	34	80.24	27
OC (%)	2.77	23	2.44	14	2.22	8	2.54	28

CV - coefficient of variation; ic: steady-state water infiltration; AHT: A horizon thickness; SLT: saprolitic layer thickness; LCD: lithic contact depth; Ks: soil saturated hydraulic conductivity; BD: soil bulk density; TP: total porosity; Mac: macroporosity; Mic: microporosity; Mgravel: medium gravel (200.00-20.00 mm); Fgravel: fine gravel (20.00-2.00 mm); ADFE: air-dried fine earth fraction (< 2.00 mm); OC: soil organic carbon.

The variability decreased, and medium and fine gravel proportion decreased, while the air-dried fine earth proportion raised with the increase in soil development (Figure 3). The structural soil quality indicators had a variable behavior with an increase in soil development. Higher variability was observed in the lower developed soils (Leptosols/Regosols) and lower variability was observed in more developed soils (Figure 4). Soil BD and Mac decreased and Mic raised with increasing in soil development at the surface soil layer, while TP had a slight trend of increase and Ks had a variable behavior with increasing in soil development at this layer. At the subsurface layer, BD, TP, and Mac trend to increase and Mic trend to decrease with raising in soil development (Figure 4).

Figure 3 - Grain size and soil particle distribution in each soil classes of the study area.

Medium gravel (200.00-20.00 mm); Fine gravel (20.00-2.00 mm); Air-dried fine earth fraction (< 2.00 mm) (ADFE); Sand (2.00-0.05 mm); Silt (0.05-0.002 mm); Clay (< 0.002 mm).

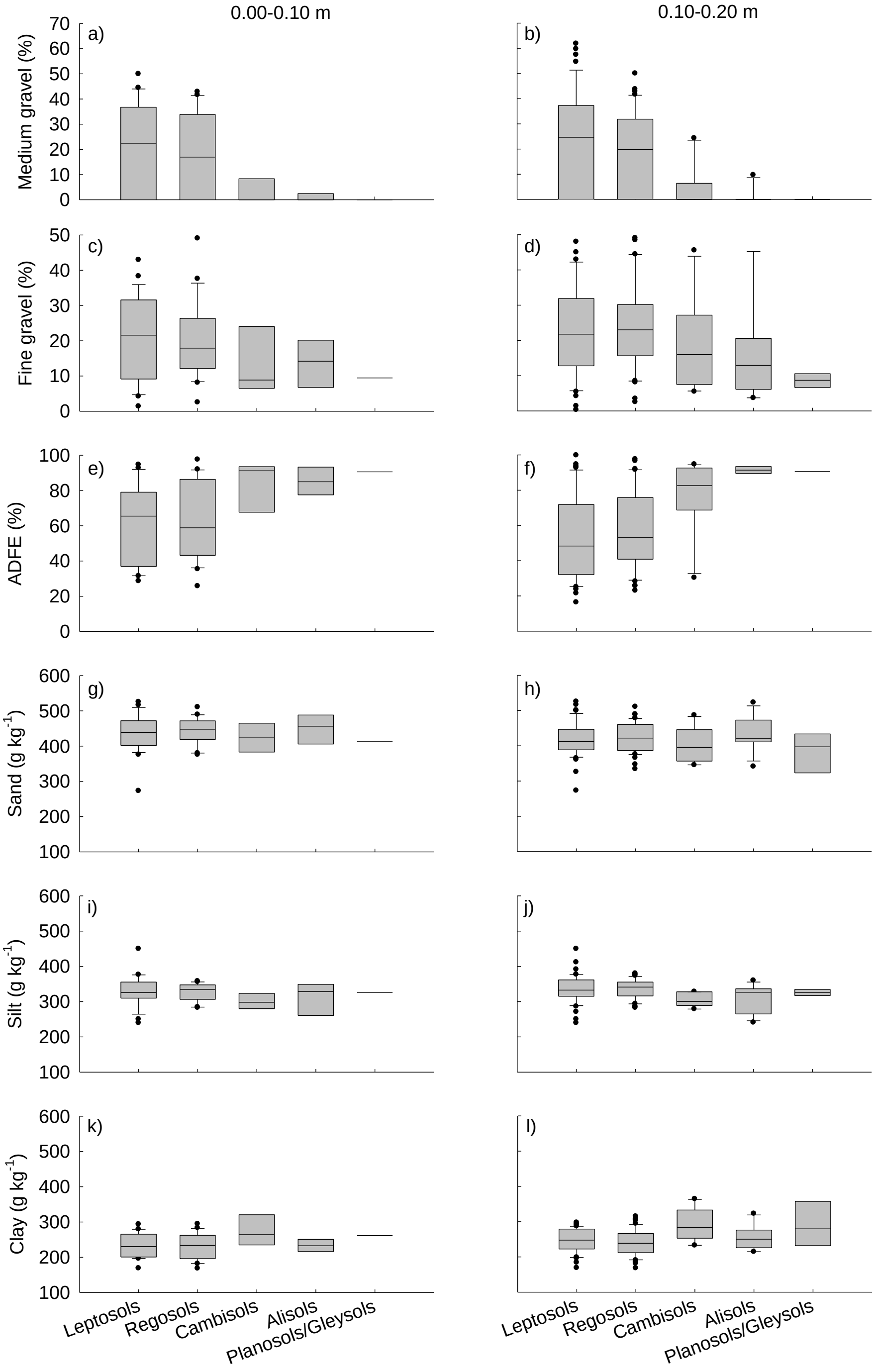
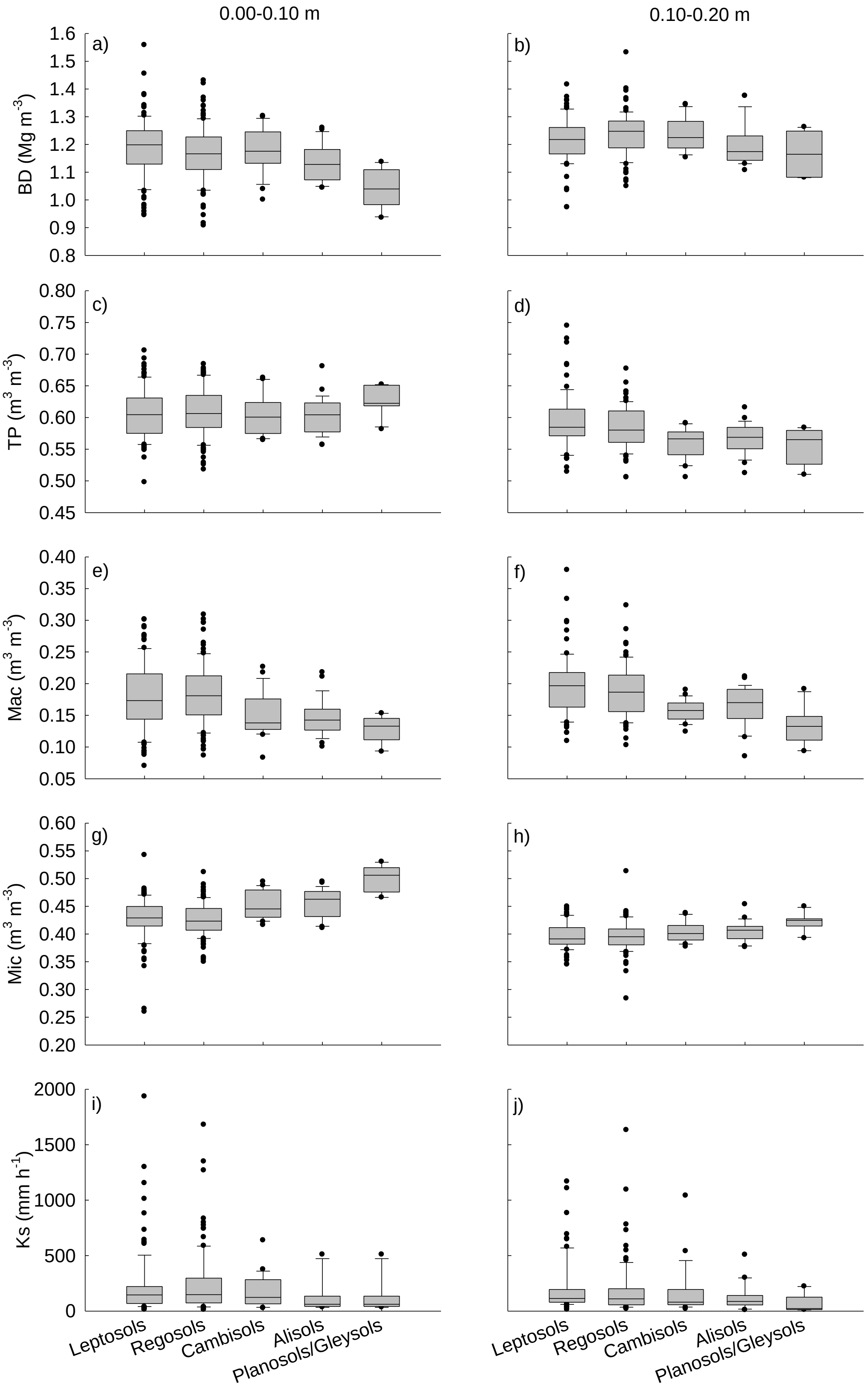


Figure 4 - Soil bulk density (BD), macroporosity (Mac), microporosity (Mic), and saturated hydraulic conductivity (Ks) within soil classes of the study area.



The Leptosols had an average A horizon thickness of 0.14 m (CV = 60%), an average saprolitic layer thickness of 0.14 m (CV = 95%), and an average lithic contact depth of 0.28 m (CV = 47%). The average of ic was 68.5 mm h^{-1} (13.1 up to 289.2 mm h^{-1}; CV = 97%). Saprolitic layer thickness, ic, Ks and medium gravel had high variability (CV > 62%) at both soil layers (Table 2).

The Regosols had an average A horizon thickness of 0.20 m (CV = 44%), an average saprolitic layer thickness of 0.50 m (CV = 25%), and an average lithic contact depth of 0.70 m (CV = 19%). The average ic was 77.0 mm h^{-1} (12.5 up to 248.2 mm h^{-1}; CV = 97%). Soil ic, Ks and medium gravel had high variability (CV > 62%) at both soil layers (Table 2).

The Cambisols had an average A horizon thickness of 0.23 m (CV = 75%), an average saprolitic layer thickness of 0.20 m (CV = 118%), and an average lithic contact depth of 0.69 m (CV = 29 %). The average ic was 71.4 mm h^{-1} (4.1 up to 71.4 mm h^{-1}; CV = 115%). Soil ic, A horizon thickness, saprolitic layer thickness, Ks and the medium and fine gravel had high variability (CV > 62%) at both soil layers (Table 2). Cambisols had high variability of fine gravel at the 0.00-0.10 m (CV = 70.92%) and the 0.10-0.20 m (CV = 65.50%) soil layers.

Most soil physical properties were similar between surface (0.00-0.10 m) and subsurface (0.10-0.20 m) layers in Leptosols, Regosols and Cambisols. The highest differences between soil layers were observed for medium and fine gravel, which were higher, and for ADFE and OC, which were smaller at the subsurface soil (0.10-0.20 m) layer in relation to the surface soil layer (0.00-0.10 m). The soil structural properties had low variability, except Mac which had mean variability at the surface layer. The particle size distribution had low variability for sand and silt and mean for clay fractions, while coarser fractions had higher variability. Soil OC had average variability at the surface layer.

Alisols had an average A horizon thickness of 0.23 m (CV = 75%), an average saprolitic layer thickness of 0.07 m (CV = 54%), and an average lithic contact depth of 1.30 m (CV = 27 %). The average ic was 130.58 mm h^{-1} (10.16 mm h^{-1} up to 538.58 mm h^{-1}; CV = 154%). Soil ic, Ks at the surface layer, fine gravel at the subsurface layer, and medium gravel at both soil layers had high variability (CV > 62%). Most soil physical properties that reflect soil structure had low variability (CV < 12%) (Table 2).

The soil properties distribution variability was consistent with the soil classes observed in the study area (Figures 5 and 6).

Figure 5 - Spatial distribution of A horizon thickness (m) (a), lithic contact depth (m) (b), saprolitic layer thickness (m) (c) and steady-state water infiltration (mm h^{-1}) (d).

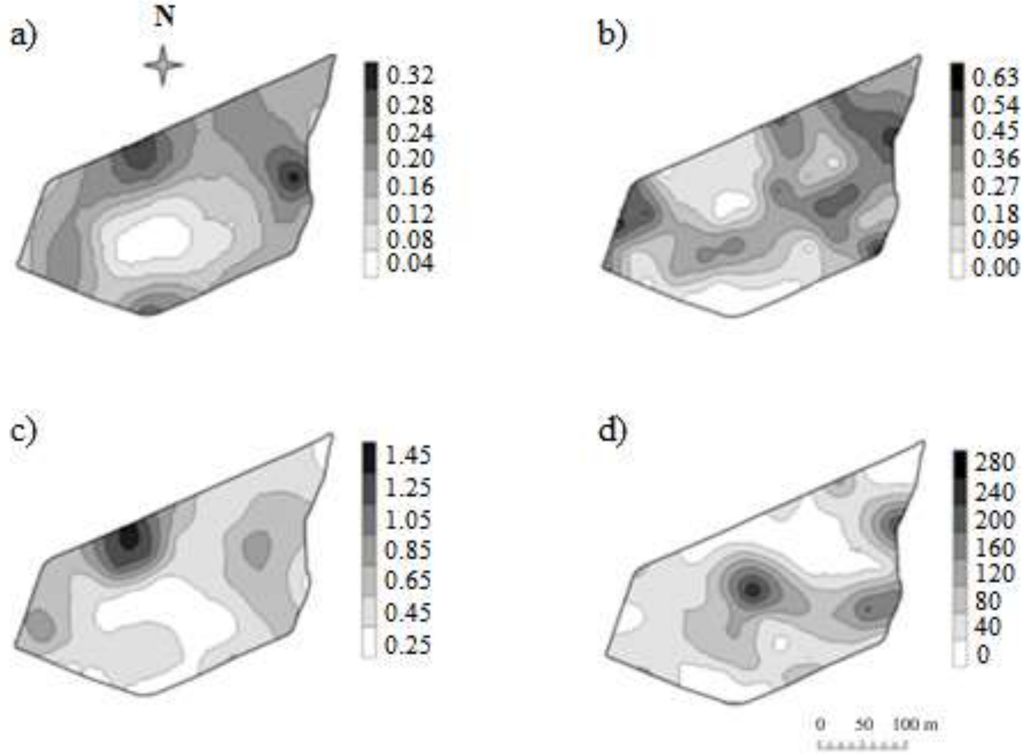
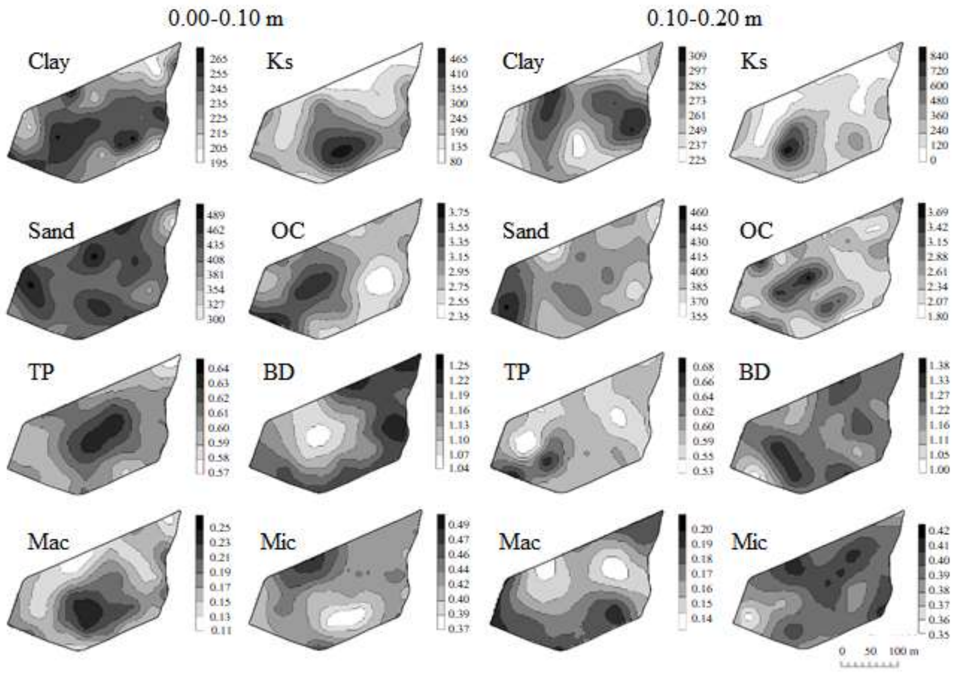


Figure 6 - Spatial distribution of clay, sand, total porosity (TP), macroporosity (Mac), microporosity (Mic), soil organic carbon (OC), bulk density (BD), and saturated hydraulic conductivity (Ks) at the 0.00-0.10 m and 0.10-0.20 m soil layers, at the study area.

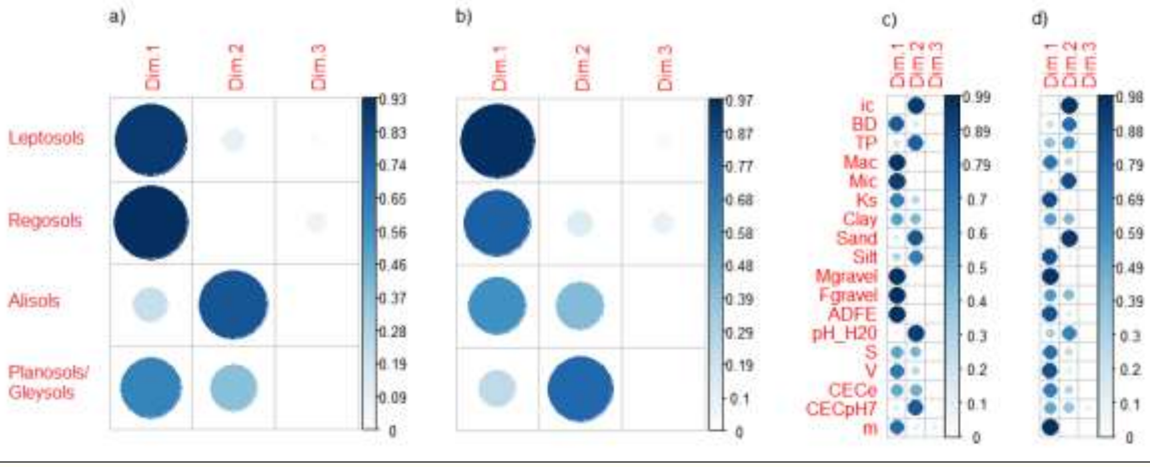


Correlation and contribution of soil physical and chemical properties for soil classes

Correlation between components (PC1 and PC2) and individuals (soils) was high for all soils, being predominantly determined by PC1 (dimension 1) for Leptosols, Regosols, and Planosols/Gleysols and by PC2 (dimension 2) for Alisols, at the surface soil layer (Figure 7a). At the subsurface layer, the correlation between components and individuals was high for Leptosols and Regosols, determined by PC1 (dimension 1) and for Planosols/Gleysols, determined by PC2 (dimension 2), while Alisols had lower correlation with the components due to the high contribution of a third component (dimension 3) (Figure 7b). Correlation between components (PC1 and PC2) and variables (soil properties) was high, being higher at the surface (Figure 7c) than in the subsurface soil layer (Figure 7d).

Figure 7 - Contribution of individuals (soils) (a, b) and variables (properties) (c, d) for the principal component analysis at the 0.00-0.10 m (a, c) and 0.10-0.20 m (b, d).

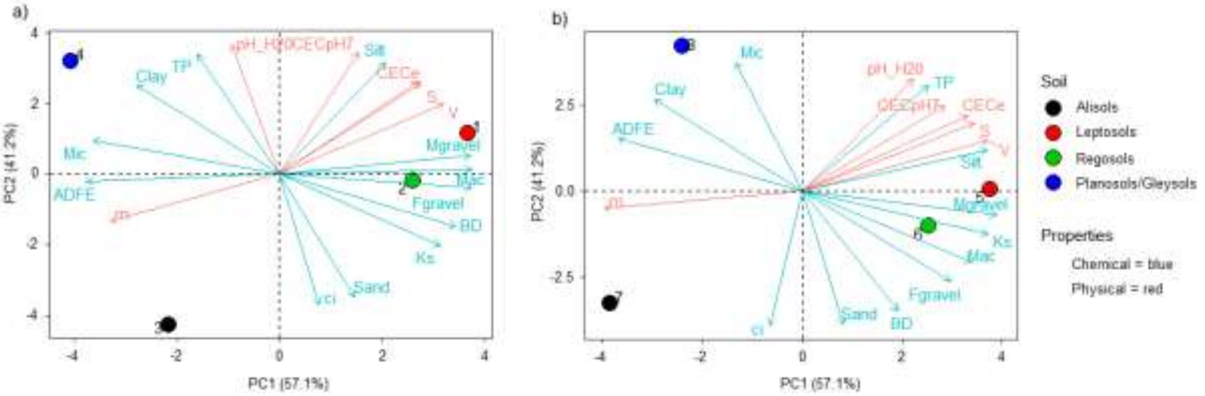
ic: steady-state water infiltration; BD: soil bulk density; TP: total porosity; Mac: macroporosity; Mic: microporosity; Ks: soil saturated hydraulic conductivity; Mgravel: medium gravel (200.00-20.00 mm); Fgravel: fine gravel (20.00-2.00 mm); ADFE: air-dried fine earth fraction (< 2.00 mm); pH_H2O: soil pH in water; S: sum of bases; V: bases saturation; CECe: effective cation exchange capacity; CECpH7: at pH 7.0 cation exchange capacity; m: aluminum saturation; Dim.: dimension.



Most part of the soil properties variance (98.3%) was explained by two principal components (PC1: 57.1%; PC2: 41.2%) which had a high explanatory power of the data (Figure 8). The Cambisols were correlated with the soil organic carbon and, to avoid the influence of this high correlation on the results quality of the other properties with the other soil classes, the Cambisols were removed from the principal component analysis.

Figure 8 - Biplot of principal component analysis at the 0.00-0.10 m (a) and 0.10-0.20 m (b) soil layers.

ic: steady-state water infiltration; BD: soil bulk density; TP: total porosity; Mac: macroporosity; Mic: microporosity; Ks: soil saturated hydraulic conductivity; Mgravel: medium gravel (200.00-20.00 mm); Fgravel: fine gravel (20.00-2.00 mm); ADFE: air-dried fine earth fraction (< 2.00 mm); pH_H2O: soil pH in water; S: sum of bases; V: bases saturation; CECe: effective cation exchange capacity; CECpH7: at pH 7.0 cation exchange capacity; m: aluminum saturation.



Leptosols had a higher correlation with medium gravel at the surface layer (0.00-0.10 m), followed by Mac and fine gravel. At this layer, the correlation was negative with ADFE (Figure 8a). At the subsurface layer (0.10-0.20 m), medium gravel had the highest correlation with Leptosols (Figure 8b). Chemical properties V, S and CEC were positively correlated and m was negatively correlated with Leptosols at the surface soil layer. At the subsurface layer, the correlation was positive with chemical properties (pH_H2O, CECpH7, CECe, S and V and negative with m (Al saturation) (Figure 8).

At the surface layer, Regosols had a positive correlation with fine gravel and Mac, followed by the medium gravel. These soils were negatively correlated with ADFE and Mic (Figure 8a). At the subsurface layer, Regosols had a high positive correlation with Ks, fine gravel and Mac, and negative with ADFE and clay content (Figure 8b). Regosols were negatively correlated with m and had a weaker correlation with other chemical properties at the surface and subsurface soil layers (Figure 8).

The Planosols/Gleysols association was positively correlated with clay content and negatively correlated with Ks at the surface layer (Figure 8a). At the subsurface layer, the correlation was positive with Mic and clay content, and negative with fine gravel and BD at the subsurface layer (Figure 8b). Soil chemical properties were not correlated with the Planosols/Gleysols association at both surface and subsurface soil layers (Figure 8).

Alisols were not positively correlated with soil physical properties at the surface and subsurface soil layers. Chemical properties were negatively correlated with Alisols at the surface and subsurface soil layers (Figure 8).

DISCUSSION

Soil properties variability

Variability and the absence of normal distribution imply morphologically distinct soils with different physical behavior at the studied area. Thus, even in small areas with slight altimetric amplitude (mean elevation of 227.54 m; CV = 0.64%), at the same physiographic region and geomorphological sites (plateau areas), relief may not be the main controlling factor for soil property variability. Although variation in relief have been considered the main factor in the formation of different soils in small areas, at the same physiographic region, where parental material, organisms, and climate have small spatial variations (WOLSKI et al., 2017), this behavior cannot be considered for Brazilian Meridional Plateau Edge of South Brazil areas, because soil classes and properties have high variability, as shown in this study. Even though relief has elevation with low altimetric amplitude, additionally to the other soil genesis factors, the detailed mapping of soil classes and the detailed soil properties characterization within soil class are necessary to understand the behavior of each soil of these land areas, due to the high soil properties variability.

Soil classes occurrence and spatial distribution

The predominance of Leptosols and Regosols with small patches of developed soils (Cambisols, Alisols, and Planosols/Gleysols) in the study area was not the expected composition, as the area is part of a characteristic plateau of the Brazilian Meridional Plateau Edge, where the Leptosols/Regosols predominate on the steep slopes of the landscape (BENITES et al., 2007), instead of on the areas under low altimetric amplitude (flat up to smooth undulating relief) (PEDRON and DAMOLIN, 2011).

The occurrence of homogeneous and more developed soils, such as the Alisols with some Cambisols, and with Planosols and Gleysols at small low land/depressions portions or where water emerging (PEDRON et al., 2006; BENITES et al., 2007; PEDRON and DALMOLIN, 2011), was the expected behavior in the study area. This occurrence was expected due to the low altimetric amplitude (flat up to smooth undulating) associated with the intensive land-use for agricultural activities in the small farms, which is generally performed at homogeneous areas in this region. In this condition, the other constant soil formation factors favor the water infiltration and percolation through the soil profile (NICÓTINA et al., 2011; PETERMAN et al., 2014) and, consequently, soil development (GRAHAM and ROSSI, 2010).

Low developed soils at the plateau areas, different from the expected behavior, occurred possibly due to the horizontal diaclase and the low fracturing degree of rocks (LEBEDEVA and BRANTLEY, 2017; HOLBROOK et al., 2019). At the surface layers, water flow for the soil development occurs through the porous system, while in a rocky environment, the water flows in the weathering mantle, in faults, joints planes, foliation planes and diaclase fractures (Singhal and Gupta, 2009). Soil development is limited when fractures are horizontally and favored when fractures are vertically oriented, as the water flow and the transport of reagents and weathering products transport is facilitated (FLETCHER and BRANTLEY, 2010; HOLBROOK et al., 2019).

The occurrence of more developed soil such as Cambisols, Alisols, and Planosols/Gleysols, which have greater land-use capacity due to the structural properties that favor the most intensive farming activities, inserted among the Leptosols and Regosols maybe is the motivation for more intensive land-use by farmers (PEDRON et al., 2006). Nevertheless, the predominance of shallow soils and the heterogeneity of soil classes affect the spatial distribution of morphological and physical properties, especially in deeper soil layers, such as at the 0.10-0.20 m layer, where most of the Leptosols have a saprolitic layer or a lithic contact.

The heterogeneity and absence of a pattern of those properties that represent soil structure among different classes and within the same class limit the land-use suitability and difficult the land-use planning of these areas. As the shallow soils predominate in the study area, knowledge of the properties that best characterize each soil class, of the saprolitic layer characteristics and the lithic contact depth are fundamental for the evaluation of land-use capacity (PEDRON et al., 2009; 2015). The principal component analysis allowed the identification and characterization of the properties that best describe and characterize the different soils of the study area.

Characteristic-properties of soil classes

The high variability of steady-state water infiltration and saprolitic layer thickness and mean variability of A horizon thickness and lithic contact depth, associated with the positive correlation of the Leptosols with medium gravel, followed by macroporosity and fine gravel and the negative correlation with ADFE at the surface layer (0.00-0.10 m) clearly describes the environmental fragility provided by the morphological and physical soil properties resulting from the incipient development of these soils.

The decreasing in soil properties variability from the Leptosols to Regosols, and the positive correlation with fine gravel and macroporosity and negative correlation with ADFE and microporosity show a higher development of the latter compared to the former. The similar behavior of the coarse fractions and of the soil particle distribution and of the physical properties that reflect the soil structure among these soils, although with lower variability in Regosols, also implies high environmental fragility of these soils.

This fragility (morphological and physical) implies restrictions on land-use and low capacity for agriculture, even though the Leptosols and Regosols have chemical properties suitable for plant growth, with a positive correlation with most chemical properties and negative with Al saturation. The type and position of contact between soil, saprolite, and rock are more limiting to agricultural and non-agricultural land-use of shallow soils than their fertility (PEDRON et al., 2009) and increase susceptibility to degradation.

A higher development of Cambisols than Regosols was confirmed by the higher A horizon thickness and the lower saprolitic layer thickness, though the lithic contact depth was similar. Also, the high variability and the high amount of fine gravel at both soil layers (0.00-0.10 m; CV = 70.92% and 0.10-0.20 m; CV = 65.50%) observed in Cambisols was not observed in Leptosols/Regosols. The high variability and high amount of fine gravel provide high fragility for these soils, as observed for Leptosols/Regosols.

The high proportion medium and fine gravel in the soil and the low effective depth of these soils provide high susceptibility to erosion, to water stress, crop root growth, and mechanization activities (DALMOLIN et al., 2004; PEDRON and DALMOLIN, 2011).

The medium and fine gravel fractions favor soil water infiltration, however the amount of water retention and availability is low (OYONARTE et al., 1998). The high proportion of these coarse fractions in the soil and the low thickness of these soils imply a high amount of soil drainable water, which may favor water stress. This soil condition also favors the fast saturation of the soil profile, with runoff and, consequently, soil erosion.

In shallow soils, infiltration capacity and water availability are dependent on soil properties, saprolite and adjacent rock (STÜRMER et al., 2009; PEDRON et al., 2011). The higher soil saturated hydraulic conductivity observed in Leptosols/Regosols was possibly provided by the coarse fractions and the fracturing of the lithic contact in soils with the low thickness of A horizon and saprolitic layer, which favor preferential flows (STÜRMER et al., 2009). Nevertheless, the Ks and ic may be low even in sandy soils and in a highly fractured saprolitic layer (PEDRON et al., 2011). Fractures can be filled with clayey materials acting as an impediment to the volume and velocity of water that infiltrates and moves in the soil profile (STÜRMER et al., 2009).

An impeding layer, such as shallow lithic contact and the high proportion of gravel fractions (PEDRON et al., 2009) that are characteristic of most soils in the studied area, possibly affect the growth into depth, the spatial distribution, and morphology of the roots. These changes are similar to those provided by the soil compaction and affect plant growth and yield.

In shallow soils with shallow lithic contact, root growth is limited, especially, in the vertical direction (GOODSHELLER, 2010; NIE et al., 2017). Thus, root biomass increases in the topsoil (SCHWINNING, 2013), which favors the root system development instead of aerial part growth (GONÇALVES and MELLO, 2005). This behavior is different when the R (rock) and Cr (saprolite) layers have the high fracturing degree, with wide angular and fracture spacing variation (GRAHAM and ROSSI, 2010). The fractures favor water, minerals and organic materials movement into the profile, and roots penetration and development (PEDRON et al., 2009; 2010; HASENMUELLER et al., 2017), since water and nutrient are available (GRAHAM and ROSSI, 2010; HASENMUELLER et al., 2017). In these situations, the roots may undergo anatomical changes (circular or flat), induced by the shape of the pores (LIPIEC et al., 2012) or fractures. These conditions provide these soils a low land-use capacity, as plants tend to be more productive in soils with deeper lithic contact, as soil patches observed in the study area, once any other root growth restriction arise.

The higher development of Alisols in relation to the other soils is confirmed by morphological characteristics such as higher A horizon thickness, lower saprolitic layer thickness, and a deeper lithic contact. In addition, the negative correlation with chemical properties is characteristic of more weathered soils. These properties imply less susceptibility to degradation and provide a better environment for soil air, CO_2 and water flows, and plant development (BORNYASZ; GRAHAM; ALLEN, 2005; GRAHAM and ROSSI, 2010). The rooting environment provided by deep soils is homogeneous when well structured, and the roots can grow in any direction (GRAHAM and ROSSI, 2010; GOODSHELLER, 2010). The structure of Alisols probably provided higher Ks at the surface (0.00-0.10 m) than at the subsurface (0.10-0.20 m) soil layer, and lower Ks than compared to the other soil classes. The descrease in Ks with the increase in soil depth probably is caused by the lower biological activity in deeper soil layers. Although these descrese in Ks with increasing in soil depth, lower Ks than observed in this study are commonly for Alisols (BARBOSA et al., 2020).

The positive correlation of the Planosols/Gleysols association with clay content and microporosity and negative correlation with saturated hydraulic conductivity and fine gravel show the high development and the low properties variability of these soils. The high effect of clay content and of microporosity on the description of Planosols/Gleysols possibly occurred due to the significant presence of clay from the deposition of finer particles coming from higher positions to the landscape depressions, while the negative correlation with the saturated hydraulic conductivity possibly occurred due to the water emerging and the lower permeability of soil (PEDRON et al., 2006; PEDRON and DALMOLIN, 2011).

The variation of soil classes and their morphological, physical and chemical properties indicate the need for detailed soil surveys for sustainable land-use. The studied area is inserted in a complex pedogeomorphological region and is intensively used mainly by family farming. The fragility of these soils to degradation and the low capacity to agricultural production are also complex and require technical and soil spatial distribution knowledge, in order to provide a sustainable use and management of these areas.

FINAL CONSIDERATIONS

Flat areas of the Brazilian Meridional Plateau Edge in Atlantic Forest biome of South Brazil, even with low altimetric amplitude, have high variability of soil types and of morphological, physical and chemical properties, with high natural fragility. This information is important and fundamental for the proper planning of land-use and management of these areas that should not be considered as homogeneous and with high land-use capacity. In these plateau areas predominate Leptosols and Regosols, with small patches of more developed soils (Cambisols, Alisols and, Planosols/Gleysols), unlike the occurrence and characteristics of soils that were expected according to the soil-landscape relationship.

Soils in incipient formation occurring in the study area (Leptosols/Regosols) are characterized by high natural fertility, the predominance of coarse fractions (medium and fine gravels), negative correlation with air-dried fine earth fraction and aluminum saturation. These characteristics provide low land-use capacity, even with the high natural fertility, due to the high variability of the soil physical properties, the predominance of coarse fractions, the low A horizon thickness and a shallow lithic contact, which increases susceptibility to degradation. The Planosols/Gleysols association has high development and low physical properties variability, being characterized by the positive correlation with clay and air-dried fine earth fraction and negative correlation with the soil saturated hydraulic conductivity soil and the fine gravel, due to the water appearance or to the water accumulation in depressions of the landscape. Alisols were characterized by more developed soil properties that show the evolution of structure formation and by a negative correlation with soil chemical properties, which is a characteristic of weathered soils with low natural fertility.

The predominance of soils with low depth, high stony and low water retention hinder the agricultural management of the area. The high variability of soils in a relatively small area requires detailed soil surveys. This same soil variability will demand a conservationist agricultural management, directed to the soil of greatest limitation, in this case, the Leptosols, with the use of sustainable agricultural practices such as no-till, crop rotation, nutrient replacement, green fertilization, reduction of the use of agrochemicals, control of animal load and preservation of the Atlantic forest surrounding the productive areas.

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