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Original Article

Soil physical properties and root system dynamics in the Micaela sub-watershed, in Southern Brazil[1]

Propriedades físicas do solo e dinâmica do sistema radicular na sub-bacia hidrográfica Micaela, no Sul do Brasil

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HIGHLIGHTS:
- *Soil bulk density and total porosity showed spatial dependence up to 1,344 m and 560 m, respectively.*
- *Native forest areas demonstrated 53% higher root volume compared to cultivated pastures.*
- *Management systems and soil classes significantly influenced root distribution and soil organic carbon content.*

ABSTRACT: Soil physical properties and their relations with root development have become essential for the adoption of appropriate agricultural practices. Thus, soil physical attributes, root system, and soil organic carbon were evaluated in a transect under different management and soil classes. Soil physical parameters (bulk density, porosity, particle size distribution, penetration resistance), soil organic carbon, and root development (root volume, surface area, length, and average diameter) were evaluated in an 11.2 km transect. The results indicated that the bulk density, soil macroporosity, and total porosity showed a range of spatial dependence of 12 lag, 7 lag, and 5 lag, respectively, indicating that the sampling range (560 m) was adequate. Moderate to strong negative correlations ($-0.40 \le r \le -0.80$) were observed between root parameters and bulk density, penetration resistance, and sand. The correlations were positively and moderately correlated ($0.21 \le r \le 0.65$) between total porosity, soil macroporosity, soil microporosity, organic carbon, silt, clay, and root parameters. In conclusion, bulk density, penetration resistance, and sand showed greater sensitivity regarding root development than the other physical parameters. The management systems and soil classes determine root distribution and the spatial dependence of soil physical attributes.

Key words: geostatistical analysis, spatial dependence, watershed management, soil physical quality

RESUMO: As propriedades físicas do solo e suas relações com o desenvolvimento radicular tornam-se essenciais para a adoção adequada de práticas agrícolas. Assim, uma transeção sob diferentes manejos e classes de solo, atributos físicos do solo, sistema radicular e carbono orgânico do solo foram avaliados. A determinação dos parâmetros físicos do solo (densidade, porosidade, distribuição das partículas por tamanho, resistência à penetração), carbono orgânico do solo e desenvolvimento radicular (volume da raiz, área superficial, comprimento e diâmetro médio) foi realizada em uma transeção de 11,2 km. Os resultados indicaram que a densidade, macro e microporosidade e porosidade total mostraram dependência espacial de 12 lag, 7 lag e 5 lag, respectivamente, indicando que o intervalo de amostragem (560 m) foi adequado. Correlações negativas moderadas a fortes ($-0,40 \le r \le -0,80$) foram observadas entre parâmetros radiculares com a densidade do solo, a resistência à penetração e areia. Correlações positivas e moderadas ($0,21 \le r \le 0,65$) foram evidenciadas entre porosidade total, macro e microporosidade, carbono orgânico, silte, argila com parâmetros radiculares. Conclui-se que densidade do solo, resistência à penetração e areia apresentaram maior sensibilidade em relação ao desenvolvimento radicular do que os demais parâmetros físicos. Os sistemas de manejo e classes de solo determinam a distribuição radicular e a dependência espacial dos atributos físicos de solos.

Palavras-chave: análise geoestatística, dependência espacial, gestão de bacias hidrográficas, qualidade física do solo

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Introduction

Soil Physical Quality (SPQ) can be assessed by evaluating key soil properties that maintain the structural quality of the soil and increase agricultural productivity and sustainability (Bacher et al., 2019; He et al., 2023; Satriani et al., 2024; Leal et al., 2025). These properties are commonly measured through soil structures (Reichert et al., 2020), using parameters such as bulk density, macroporosity (Reis et al., 2019), particle size distribution, soil organic carbon (Bacher et al., 2019), and penetration resistance (Bünemann et al., 2018; Bacher et al., 2019; Manea et al., 2022). Additionally, root system distribution serves as an essential indicator of SPQ, as it is strongly influenced by soil conditions (Ni & Su, 2024). Therefore, the adoption of practices that improve root development depends on land use and management systems (Carducci et al., 2014; Ni & Su, 2024).

The study of roots is critical to understanding various phenomena related to shoot growth and development, but it requires a meticulous approach since evaluation methods are laborious and the roots are affected by the physicochemical variability of the soil (Vasconcelos et al., 2003). Geostatistical tools provide valuable insights into the spatial variability of soil parameters (Minai et al., 2021). Recent advancements have expanded these models to incorporate root system characteristics, enabling researchers to assess how roots respond to transient changes induced by soil management practices and their interaction with meteorological conditions (Abramowitz et al., 2008; Ni & Su, 2024).

Considering the need for knowledge involving the relationship between soil and roots, especially in watershed areas, this study was conducted in the Micaela sub-watershed (MsW), part of the Fragata Moreira watershed (FMW) in Pelotas, Rio Grande do Sul, Brazil. This region holds significant agricultural and hydrological importance, supporting rural farmers who primarily practice conventional or minimum-tillage methods. Implementing sustainable soil management practices is critical to mitigating the adverse effects of improper land use and enhancing crop productivity (Al-Shammary et al., 2024). This research aimed to investigate the spatial relationships between soil physical properties and root system development along an 11.2 km transect in the Micaela sub-watershed, examining how different management systems and soil classes influence root distribution patterns.

Material and Methods

The study was conducted in the Micaela sub-watershed (MsW), located within the Fragata Moreira watershed, situated in the rural area of Pelotas, Rio Grande do Sul, Brazil (31° 37’ 50.32” S and 52° 31’ 28.15” W). The MsW has a drainage area of 37.32 km² and an elevation range of 22 to 334 m a.s.l. (Figure 1). Based on the Köppen classification, the predominant climate is a humid subtropical climate (Cfa), with a mean annual precipitation of 1,393.9 mm and a mean annual temperature of 18.6 °C (Klumb, 2018).

The soils were mapped on a scale of 1:100.000 (Cunha et al., 2006). The soil profiles were classified according to Soil Survey Staff (2022) as Typic Albaqualf - Typic Hapludult Association, Typic Hapludult - Typic Hapludalf Association, and Lithic Udorthent - arenic Hapludult Association (Figure 1B). The classes in the Brazilian Soil Classification System are respectively: Associations: “Planossolo Háplico eutrófico - Argissolo Acinzentado eutrófico; Argissolo Vermelho Amarelo distrófico - Argissolo Vermelho Amarelo eutrófico and Neossolo Litólico distrófico - Argissolo Amarelo distrófico” (Santos et al., 2025). Table 1 presents the soil classes, particle size distribution, soil texture, and soil organic carbon (SOC).

The percentages for the soil management systems along the FMW are: cultivated pasture (18%), cropland (15%), native forest (42%), and native grassland (25%) (Figure 1). The main land uses along the transect in the MsW consisted of cultivated pastures (CP: 21%), cropland (CL: 16%), native forest (NF: 26%), and native grassland (NG: 37%) (Figure 1).

An 11.2 km spatial transect was established in the MsW. The transect encompasses a range of soil classes and diverse land uses (Figure 1). Along the transect, 101 sampling points equidistant from each other were established (112 m). Disturbed and undisturbed soil samples were taken from the 0.00-0.10 m soil layer. Sampling was performed using volumetric rings (0.05

A. B. C.

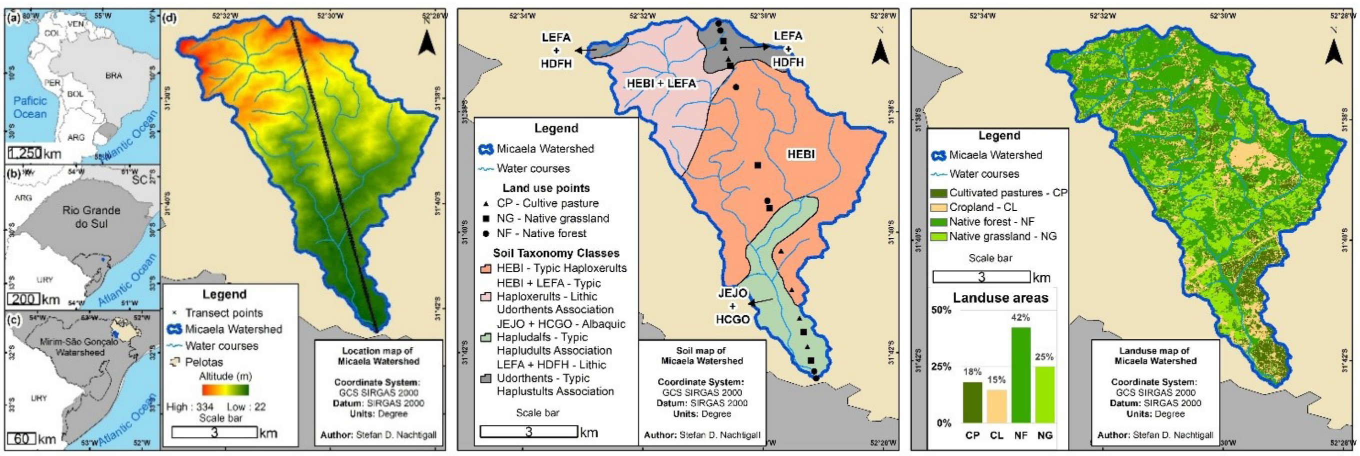

Figure 1. Location of the Micaela sub-watershed inserted in the Fragata Moreira watershed, Pelotas, RS, Brazil. The figure presented an 11.2 km spatial transect and 101 sampled points (A); soil mapping and management systems along the spatial transect (81 sample points) (B); percentage for soil management systems along the watershed (C)

Table 1. Soil classes, particle size distribution (sand, silt, and clay), texture, and soil organic carbon (SOC)

Soil classes	Sand	Silt	Clay	Texture	SOC
		(g kg^{-1})			(g kg^{-1})
Typic Albaqualf - Typic Hapludult Association	617.25	227.84	154.91	sandy loam	21.38
Typic Hapludult - Typic Hapludalf Association	629.78	215.16	155.06	sandy loam	19.58
Lithic Udorthent - arenic Hapludult Association	614.61	216.68	168.71	sandy loam	24.88

m diameter and 0.05 m height). The undisturbed samples were utilized to evaluate bulk density, total porosity, macroporosity, microporosity, and penetration resistance. The undisturbed samples were saturated through capillarity for 24 hours and balanced at a matric potential of -6 kPa using a tension table. The soil macroporosity, microporosity, and total porosity were then determined in the laboratory. These same samples were saturated through capillarity for 24 hours and balanced at a matric potential of -10 kPa using pressure chambers in the laboratory; penetration resistance (PR) was then evaluated. The PR was measured at three points equidistant from the center of the undisturbed sample, with a penetration rate of 10 mm min^{-1} (Bradford, 1980), using an electronic penetrometer MA 933 (Marconi Ltda).

After determining the PR, the samples were dried in an oven at 105 °C for a minimum period of 24 hours to calculate the bulk density (Bd) and gravimetric water content (Blake & Hartge, 1986; Gardner, 1986). Disturbed samples were used to measure soil particle size distribution (Gee & Bauder, 1986) and total organic carbon (TOC) (Table 1). The TOC was analyzed by the wet combustion method (Teixeira et al., 2017).

The root system in the soil surface layer (0.00–0.10 m) was evaluated considering soil classes and land uses along the transect (three soil classes × three land uses × two replicates). The percentage destined for grazing animals is 58% (21% cultivated pasture and 37% native grassland). The native forest was chosen as a reference because it corresponds to 25% of the total área and presents a high abundance of root systems of native species, higher soil organic matter content, and soil total porosity and lower bulk density.

The root system was evaluated using adaptations and the profile analysis technique, as described by Jorge & Silva (2010). The method consisted of opening a trench of 0.50 × 0.30 m along the transect. Previously selected points are subsequently exposed to the existing roots by washing with water. A metal grid (reticulated frame) (Figure 2) was positioned in the soil profile, and images were captured with a digital camera to represent the root distribution up to a depth of 0.10 m. The images were partially processed, adjusted, and aligned using Photoshop CS6 12.0.4 software.

For the analysis of the root parameters, the images inserted in Photoshop CS6 12.0.4 were selected and evaluated using the Safira software. The thresholding technique was used to process the images and quantify the root volume (mm³), root surface area (mm²), length (mm), and root mean diameter (mm).

Soil attributes were evaluated by analysis of classical descriptive statistics and the Kolmogorov-Smirnov normality test (KS) at a 5% significance level. The adherence of the data series and normal distribution was evaluated. The attributes presenting no normality were disregarded.

The autocorrelation function [r(j)] was calculated to verify and quantify the spatial dependence of soil attributes along the transect (Reichardt & Timm, 2020). The cross-correlation function [rc(j)] was calculated between PR and all variables for which [r(j)] revealed a spatial dependence structure. The [rc(j)] was evaluated assuming PR as a predictor variable, since this soil physical attribute is difficult to measure on a large scale. Thus, it is necessary to explore its spatial relationships with other soil attributes easily found in databases. Therefore, it will allow for the generation of mathematical models for estimating PR.

The values of [r(j)] and [rc(j)] can be affected by the path chosen through the spatial transect; hence, the data sets were organized from the west-north direction along an 11.2-km spatial transect (from point 101 to the first point). The confidence interval (CI) for the evaluation of the significance level of the values [r(j)] and [rc(j)] was calculated in both functions.

A two-factor factorial Anova was employed at the points in the spatial transect to evaluated the effects of soil classes: Typic Albaqualf - Typic Hapludult Association (Planossolo Háplico eutrófico - Argissolo Acinzentado eutrófico); Typic Hapludult - Typic Hapludalf Association (Argissolo Vermelho Amarelo distrófico - Argissolo Vermelho Amarelo eutróficos), and Lithic Udorthent - arenic Hapludult Association (Neossolo litólico distrófico - Argissolo Amarelo distrófico), as well as soil management (native grassland, cultivated pasture, and native forest) on root variables. The analyzed factors were soil classes and management systems. Each factor had three levels and two replicates. The root volume, root surface area,

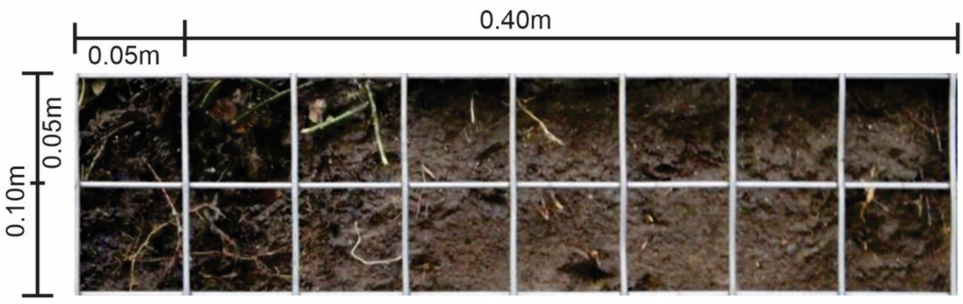

Figure 2. Metal grid (reticulated frame: 0.40 x 0.10 m) for sampling of the root system development in the soil profile (0.00–0.10 m) within the spatial transect of sub-watershed Micaela

length, and root mean diameter were dependent variables. The factors and interactions with significant effects were compared using Tukey's test. Linear correlations between soil physical parameters and root volume, root surface area, length, and root mean diameter were evaluated using the Spearman correlation test. The statistical analyses were performed using the R software (R Core Team, 2021).

Results and Discussion

The descriptive statistics for soil parameters along the transect in the MsW region are displayed in Table 2. The PR exhibited significant variations across measurements, ranging from 0.73 MPa (in native forest) to 3.93 MPa (in cultivated pasture), with a general average of 1.99 MPa. The average bulk density (BD) value was 1.40 Mg m^{-3}, ranging from 0.87 Mg m^{-3} (native forest) to 1.73 Mg m^{-3} (cultivated pasture). The soil macroporosity (Macro) and total porosity (TP) varied from 2.02 to 28.28% and 25.18 to 62.36%, with mean values of 11.53 and 43.31%, respectively. The soil organic carbon (SOC) varied from 8.20 g kg^{-1} (cropland) to 33.5 g kg^{-1} (native forest), with a mean value of 20.03 g kg^{-1} (Table 2). The observed patterns arise from land use management systems interacting with natural soil variability across the landscape, where root activity, organic matter dynamics, and compaction processes shape the spatial distribution of soil properties, informing sustainable land use planning in the region (Peixoto et al., 2019; Silva et al., 2021; Zanchin et al., 2021a).

The results of the particle size distribution (sand, silt, and clay) and soil organic matter (Table 2) are consistent with the soil classes of this region (Table 1). In terms of the asymmetry, only bulk density and sand content exhibited a negative symmetry (Table 2), in which the average shifted to the right side. This behavior occurs because most of the observed points are concentrated on the right side of the probability distribution of the results. The silt and clay content did not present normality when using the Kolmogorov-Smirnov test at a 5% significance level (Table 2). Therefore, these variables were subjected to an autocorrelation test.

The function r(j) indicates spatial dependence between adjacent observations of the variable along the transect. Furthermore, in all cases, the soil variables presented autocorrelation and spatial dependence, indicating an adequate sampling scale. The BD, Macro, and TP (Figures 3B, C, and D) showed a range of spatial dependence of 12 lag (1,344 m), 7 lag (784 m), and 5 lag (560 m), respectively, indicating that the sampling range utilized in this study (560 m) was adequate. The sampling scale adopted was smaller

Table 2. Descriptive statistics for the soil variables along the transect in the MsW, Southern RS, Brazil

Variables	Mean	Min.	Max.	S.D.	CV	Skew	Kurt	KS
PR (MPa)	1.99	0.73	3.93	0.59	29.43	0.46	3.67	0.66**
BD (Mg m^{-3})	1.40	0.87	1.73	0.19	13.33	-0.62	2.99	0.30**
Macroporosity (m^3 m^{-3})	0.12	0.20	0.28	5.91	51.29	0.75	2.99	0.16**
TP (m^3 m^{-3})	0.43	0.25	0.62	7.06	16.30	0.34	3.21	0.71**
Sand (g kg^{-1})	596.15	310.00	821.67	91.57	15.36	-0.92	4.14	0.20**
Silt (g kg^{-1})	222.91	131.14	424.15	52.91	23.74	1.36	5.61	0.02
Clay (g kg^{-1})	180.94	47.19	519.19	74.84	41.36	2.16	9.08	0.01
SOC (g kg^{-1})	20.03	8.20	33.50	5.11	25.53	0.27	3.11	0.63**

Min. - Minimum; Max. - Maximum; S.D. - Standard deviation; C.V. - Coefficients of variation (%); Skew. - Skewness; Kurt. - Kurtosis; KS - Kolmogorov-Smirnov test; **: p-value > 0.05. [2]PR - Penetration resistance; BD - Bulk density; TP - Total porosity; SOC - Soil organic carbon

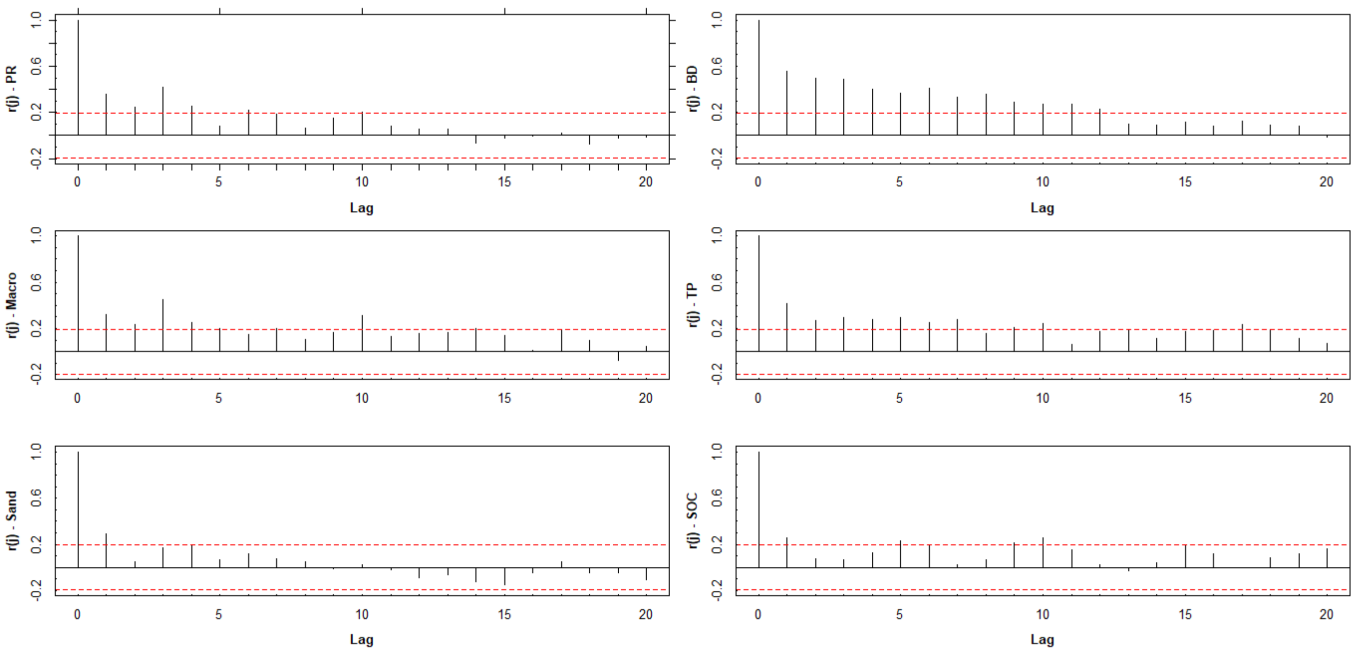

Figure 3. Autocorrelation functions of soil variables along the transect in the MsW, southern RS, Brazil. PR - Penetration resistance (MPa); BD - Bulk density (mg m^{-3}); Macro - Soil macroporosity (m^3 m^{-3}); TP - Total porosity (m^3 m^{-3}); Sand (g kg^{-1}); SOC - Soil organic carbon (g kg^{-1})

than the spatial dependence, ensuring that soil variations were measured accurately. The autocorrelation of PR was observed up to 4 lag (1 lag = 112 m) (Figure 3A), totaling dependence of up to 448 m, considering values of r(j) higher than the CI = 0.195 (dotted line). This indicates the definition of the zone of influence of the variable in space, optimizing the sampling, soil, and root characteristics indicated. The observed variations can be explained by natural factors, human activities, soil loss, and biological processes that collectively generate soil spatial dependence (Zanchin et al., 2021b; Laurenti et al., 2024).

The BD, Macro, TP, and SOC presented spatial correlation with PR (Figures 4A, B, C, and E). The cross-correlogram between PR and BD showed a spatial dependence between them of 8 lag to the positive direction and 9 lag (Figure 4A). The PR and macroporosity (Figure 4B) presented a negative cross-correlation between them up to 4 lag (448 m) in both directions. The PR and TP revealed negative cross-correlation, with a 10 lag to the right direction (Figure 4C). For example, [PR(xi), TP(xi+j)] were correlated in the right direction (j = +10 lag), whereas the cross-correlation remained until 12 lag (j = −12 lag) towards the lag delay (left direction). Regarding the negative and spatial cross-correlations of PR with SOC, a higher spatial dependence was observed between the variables up to a 3 lag (336 m) (Figure 4E).

Table 3 presents the analysis of the management system's influence on the root parameters evaluated along the transect. The root volume (V) had a significant difference between Typic Albaqualf - Typic Hapludult Association and Typic Hapludult - Typic Hapludalf Association, in which the highest root volume was indicated under the native forest. Regarding interaction, only V and SA showed a significant difference in the soil classes and management system (Table 4). The lowest mean SA values were found in the Typic Albaqualf - Typic Hapludult Association in cultivated pasture and in the Typic Hapludult - Typic Hapludalf Association in cultivated and native pasture.

Significant Spearman correlations were observed between root parameters (V, SA, MD, and L) and soil structure (BD, PR, and sand), with moderate to strong negative correlations ($-0.40 \leq r \leq -0.80$) (Table 5). The TP, Macro, Micro, SOC, silt, and clay were positively and moderately correlated ($0.21 \leq r \leq 0.65$) with root parameters. The root length was the attribute most correlated with BD, TP, soil macroporosity, PR, and

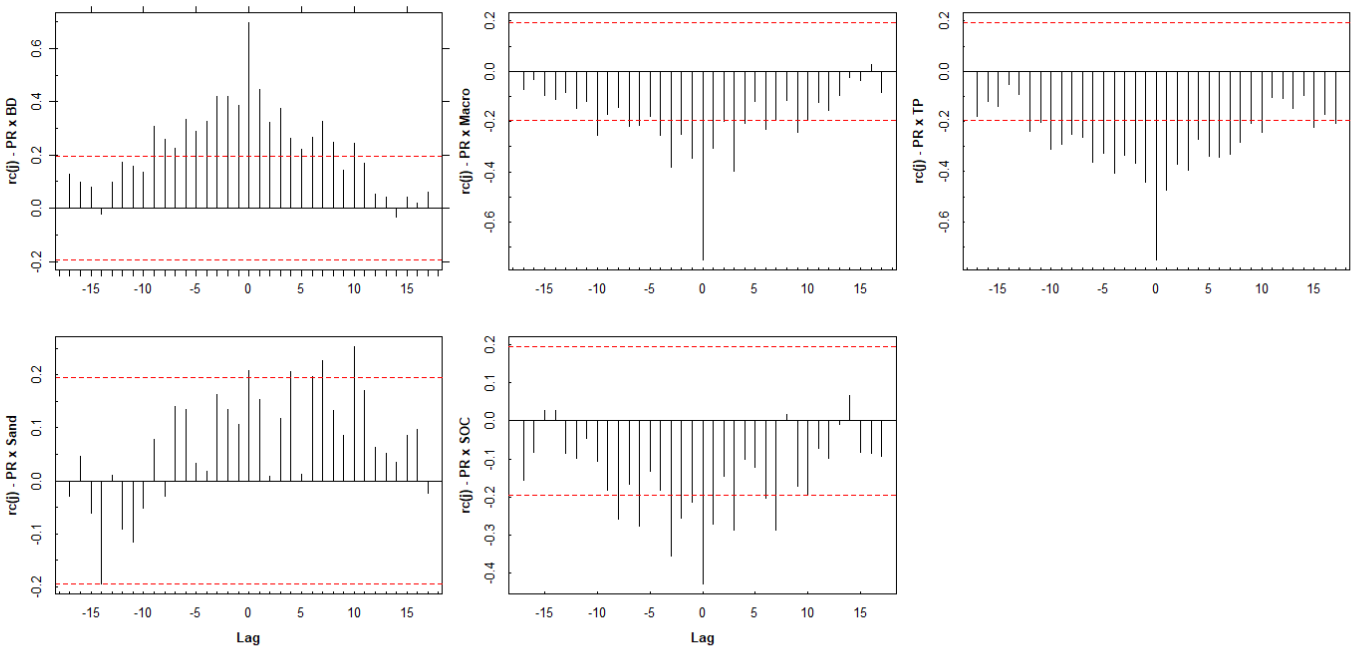

Figure 4. Cross-correlation functions of the penetration resistance (PR, MPa) with soil variables[1] along the transect in the MsW, southern of RS, Brazil. BD - Bulk density (Mg m^{-3}); Macro - Soil macroporosity (m^3 m^{-3}); TP - Total porosity (m^3 m^{-3}); Sand (g kg^{-1}); SOC - Soil organic carbon (g kg^{-1})

Table 3. Effect of soil management[1] on the root volume (V), root surface area (SA), root mean diameter (MD), and root length (L) along the transect in the MsW, Southern of RS, Brazil

	V (mm^3)	SA (mm^2)	MD	L
			(mm)	
Typic Albaqualf - Typic Hapludult Association	973.35 a	2802.44	1.06	965.9
Typic Hapludult - Typic Hapludalf Association	282.2 b	1124.41	0.73	390.99
Lithic Udorthent - arenic Hapludult Association	569.49 ab	2406.82	0.73	880.53
	*		ns	
CP	419.37 b	1603.94	0.55 b	542.16
NG	506.03 ab	1729.21	0.82 ab	610.58
NF	899.64 a	3000.52	1.15 a	1084.67
$p \leq 0.05$	*	ns	*	ns

[1]CP - Cultivated pasture; NG - Native grassland; NF - Native forest. Mean values with distinct letters between lines are significantly different ($p \leq 0.05$). Tukey test was employed to compare the means; * - Significant difference; ns - Non-significant

Table 4. Interaction of the soil classes and management system[1] on the root volume (V), root surface area (SA), root mean diameter (MD), and root length (L) along the transect in the MsW, Southern of RS, Brazil

Soil classes		V (mm^3)	SA (mm^2)	MD	L
				(mm)	
Typic Albaqualf - Typic Hapludult Association	CP	318.8 b	1233.3 b	0.6	417.9
	NG	681.9 b	1691.1 a	1.1	481.5
	NF	1919.4 a	5482.9 a	1.5	1998.3
Typic Hapludult - Typic Hapludalf Association	CP	68.8 b	331.7 b	0.4	130.7
	NG	320.2 b	1088.3 b	0.7	338.7
	NF	457.7b	1953.2 a	1.1	703.6
Lithic Udorthent - arenic Hapludult Association	CP	870.5 b	3246.8 a	0.7	1077.9
	NG	516.1 b	2408.2 a	0.6	1011.6
	NF	321.9 b	1565.4 a	0.9	552.1
		*			ns

V - Root volume; AS - Root surface area; MD - Root mean diameter; L - Root length; CP - Cultivated pasture; NG - Native grassland; NF - Native forest; * - Significant difference; ns - Non-significant difference. Mean values with distinct letters between lines are significantly different ($p \leq 0.05$). Tukey test was employed to compare the means.

Table 5. Correlation root volume (V), root surface area (SA), root mean diameter (MD), root length (L), and soil variables[1] along the transect in the MsW, southern RS, Brazil

	BD	TP	Macro	Micro	PR	SOC	Sand	Silt	Clay
V	-0.502*	0.433*	0.367*	0.367*	-0.683*	0.400*	-0.617*	0.317*	0.333*
SA	-0.594*	0.467*	0.467*	0.250*	-0.717*	0.533*	-0.400*	0.383*	0.133*
MD	-0.301*	0.617*	0.383*	0.583*	-0.633*	0.333*	-0.550*	0.217*	0.417*
L	-0.695*	0.567*	0.583*	0.267*	-0.800*	0.650*	-0.433*	0.367*	0.167*

[1]BD - Bulk density (Mg m^{-3}); TP - Total porosity (m^3 m^{-3}); Macro - Soil macroporosity (m^3 m-$^{-3}$); Micro - Soil microporosity (m^3 m^{-3}); PR - Penetration resistance (MPa); SOC - Soil organic carbon (g kg^{-1}). * - Significant ($p < 0.05$)

SOC. The PR was the one that showed the best correlation with root length. These results mechanically limit root growth; however, SOC and macroporosity can compensate for these limitations, improving conditions for root expansion (Bengough et al., 2011). Penetration resistance can strongly inhibit root development (-0.80) rather than soil porosity and organic matter (0.65).

According to the classification of Wilding & Drees (1983), PR, TP, sand, silt, and SOC exhibited moderate variability (15% < CV ≤ 35%), while macroporosity and clay showed high variability (CV > 35%). The BD presented low variability along the transect (CV ≤ 15%) (Table 2). Timm et al. (2006) characterized the spatial patterns of BD along a spatial transect in an area under coffee cultivation subjected to wetting/drying cycles. The authors concluded that BD presented low CV values, ranging from 3.8 to 4.5% in some cycles, indicating that the observations of this variable showed higher spatial homogeneity and are dependent on soil water content. The highest values of PR and BD were found in the cultivated pasture, possibly due to trampling by grazing animals (Table 2). These values can indicate soil compaction, which limits the development of the root system; restrictive values of PR > 2 MPa are detrimental to crop development (Benevenute et al., 2020).

In contrast, the highest values of TP and Macro were found in the native forest (Table 2). Areas under the native forest are characterized by higher SOC, macro, and TP. An increase in SOC provides a better soil structure, increasing porosity and decreasing BD (Lopes et al., 2020), corroborating the values obtained in the study. Areas under cropland presented a lower SOC due to intensive soil preparation. Soil structure disaggregation under intensive management also contributes to higher organic matter oxidation and the release of carbon dioxide into the atmosphere, intensifying the greenhouse effect (Feng et al., 2020).

The knowledge of the spatial distribution of PR (Figure 3) may be helpful to identify soil compaction at the watershed level, aiding in decision-making to increase agricultural productivity. It can contribute to modeling other soil functions within the ecosystem. Wang & Shao (2013) encountered spatial auto-correlations of BD, TP, and macro up to 150 m. Land use has a significant effect on the distribution and spatial dependence of BD and TP on a watershed scale (Soares et al., 2020). Centeno et al. (2020) also found spatial dependencies for the parameters BD and Macro up to 2 lag (1 lag = 150 m) along a spatial transect established in the watershed.

The cross-correlations between PR and Macro, and between TP and SOC, exhibited an inverse spatial correlation with PR along the transect (Figure 4). This result may be related to a larger porous system and organic carbon content. This effect contributes to a better physical structure, allowing a reduction in PR. Studies have found a positive correlation between BD and PR in agricultural systems (Reichert et al., 2020). The attributes presenting a higher correlation with PR and spatial dependence structure were BD, macro, TP, and SOC. These variables have the most significant potential as covariates to generate predictive models of PR on a watershed scale.

The Albaqualf provides the highest root development of vegetation in the surface layer, mainly due to the higher availability of water, organic matter, and high cation exchange capacity. All the variables presented above help in good root development. The higher root volume (V) and mean root diameter (MD) in the native forest are explained by the presence of larger shrub plants and greater vegetative diversity in tropical climate forests (Table 3), which exhibit greater biomass and root development (Hertel et al., 2009). Areas under cultivated pasture present pressure caused by animal trampling and tillage, which compromises root development.

The higher volume indicated a more expressive interaction in an area under the native forest in the Typic Albaqualf - Typic

Hapludult Association (Table 4). This soil use stimulates the development and concentration of roots in its surface layers. The native forest has a more aggressive root system, with higher organic carbon content from 0.00 to 0.10 m (Gotardo et al., 2020). The higher root abundance may be correlated with higher organic matter concentrations, which are commonly found in the surface layer. Root abundance may also be associated with favorable physical conditions (Machado et al., 2018).

The lowest averages of root surface area were observed under the cultivated pasture and native grassland in the Typic Hapludult - Typic Hapludalf Association (Table 4), which is mainly characterized by lower drainage. Panayiotopoulos et al. (1994), Benevenute et al. (2020), and Kumi et al. (2023) found negative correlations between BD, PR, and sand with V, SA, MD, and L. The increase in BD and PR resulted in a reduction of all parameters of root growth ($-0.84 \leq r \leq -0.96$), including the number of roots, total and average root length, root elongation rate, and both wet and dry root weight. In general, soils with poor drainage and high compaction severely impair root development (Bengough et al., 2011).

Table 5 shows a positive correlation between TP, Macro, Micro, SOC, silt, clay, and root variables. An example of this positive relationship was reported by Banks et al. (2020), who found correlations between Macro and V ($r = 0.86$), indicating an abundance of root parameters, adequate macroporosity, and healthy root development in crops. This study highlights the relationships between soil physical properties and root dynamics, suggesting that future studies should focus on predicting PR through soil attributes and include them in biological variables of hydrological models to optimize soil and water conservation in watersheds.

Conclusions

1. The management systems and soil classes influence root distribution and the spatial dependence of soil physical attributes. The bulk density, soil macroporosity, and total porosity showed a range of spatial dependence of 12, 7, and 5 lag, respectively, indicating that the sampling range (560 m) was adequate.

2. The management systems with reduced soil disturbance (native forest) area showed the highest root volume, with 53% greater than cultivated pastures and 43.75% higher than native pasture, mainly considering Typic Albaqualf - Typic Hapludult association.

3. The moderate to strong negative correlations ($-0.40 \leq r \leq -0.80$) were observed between root parameters with bulk density, penetration resistance, and sand. Positive and moderate correlations ($0.21 \leq r \leq 0.65$) were observed between total porosity, soil macroporosity, soil microporosity, and organic carbon, silt, and clay and root parameters. In conclusion, bulk density, penetration resistance, and sand showed greater sensitivity regarding root development than the other physical parameters.

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Literature Cited

Abramowitz, G.; Leuning, R.; Clark, M.; Pitman, A. Evaluating the performance of land surface models. Journal of Climate, v.21, p.5468–5481, 2008. https://doi.org/10.1175/2008JCLI2378.1.

Al-Shammary, A. A. G.; Al-Shihmani, L. S. S.; Fernández-Gálvez, J.; Caballero-Calvo, A. Optimizing sustainable agriculture: A comprehensive review of agronomic practices and their impacts on soil atributes. Journal of Environmental Management, v.364, e121487, 2024. https://doi.org/10.1016/j.jenvman.2024.121487.

Bacher, M. G.; Schmidt, O.; Bondi, G.; Creamer, R.; Fenton, O. Comparison of soil physical quality indicators using direct and indirect data inputs derived from a combination of in-situ and ex-situ methods. Soil Science Society of America Journal, v.83, p.5–17, 2019. https://doi.org/10.2136/sssaj2018.06.0218.

Banks, R.; Wendling L.; Basford K.; Ringrose-Voase A.; Banks V. Beneficial soil profile differences associated with tropical grass pastures on sodic texture contrast soils in Northern New South Wales. Soil Research, v.58, p.207-218, 2020. https://doi.org/10.1071/SR19140.

Benevenute, P. A. N.; Morais, E. G. de; Souza, A. S.; Vasques, I. A. S.; Cardoso, D. P.; Sales, F. R.; Severiano, E. C.; Homem, B. G. C.; Casagrande, D. R.; Silva, B. M. Penetration resistance: An effective indicator for monitoring soil compaction in pastures. Ecological Indicators, v.117, e106647, 2020. https://doi.org/10.1016/j.ecolind.2020.106647.

Bengough, A. G.; McKenzie, B. M.; Hallett, P. D.; Valentine, T. A.; Root elongation, water stress, and mechanical impedance: a review of limiting stresses and beneficial root tip traits. Journal of Experimental Botany, v.62, p.59-68, 2011. https://doi.org/10.1093/jxb/erq350.

Blake, G. R.; Hartge, K. H. Particle density. In: Klute, A. (2nd ed.) Methods of soil analysis. Soil Science Society of America, 1986. p.377-382.

Bünemann, E. K.; Bongiorno, G.; Bai, Z.; Creamer, R. E.; Deyn, G.; Goede, R.; Fleskens, L.; Geissen, V. Kuyper, T. W.; Mäder, P.; Pulleman, M.; Sukkel, W.; Groenigen, J. W.; Brussaard, L. Soil quality – a review. Soil Biology Biochemistry, v.120, p.105-125, 2018. https://doi.org/10.1016/j.soilbio.2018.01.030.

Carducci, C. E.; Oliveira, G. C.; Curi, N.; Heck, R. J.; Rossoni, D. F.; Carvalho, T. S. de; Costa, A. L. Gypsum effects on the spatial distribution of coffee roots and the pores system in oxidic Brazilian Latosol. Soil and Tillage Research, v.145, p.171-180, 2014. https://doi.org/10.1016/j.still.2014.09.015.

Centeno, L. N.; Timm, L. C.; Reichardt, K.; Beskow, S.; Caldeira, T. L.; Oliveira, L. M. de; Wendroth, O. Identifying regionalized co-variate driving factors to assess spatial distributions of saturated soil hydraulic conductivity using multivariate and state-space analyses. Catena, v.191, e104583, 2020. https://doi.org/10.1016/j.catena.2020.104583.

Cunha, N. G.; Silveira, R. J. C. Solos e terras do planalto Sul-Rio-Grandense e planícies costeiras. EMBRAPA/CPACT (Documentos, 55/06). Pelotas: Ed. UFPel, 43p, 2006. https://www.embrapa.br/busca-de-publicacoes/-/publicacao/862649/solos-e-terras-do-planalto-sul-rio-grandense-e-planicies-costeiras.

Feng, Q.; Chunjiang, A.; Zhi, C.; Zheng, W. Can deep tillage enhance carbon sequestration in soils? A meta-analysis towards GHG mitigation and sustainable agricultural management. Renewable and Sustainable Energy Reviews, v.133, e110293, 2020. https://doi.org/10.1016/j.rser.2020.110293.

Gardner, W. H. Water content. In A. Klute (Ed.), Methods of soil analysis, Part 1: Physical and mineralogical methods (2nd ed.). Soil Science Society of America, American Society of Agronomy, 1986. p.493-544.

Gee, G. W.; Bauder, J.W. Particle-Size Analysis. In: Klute, A.; Ed., Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods, Agronomy Monograph (No. 9, 2nd ed.). American Society of Agronomy/Soil Science Society of America, 1986. p.383-411.

Gotardo, R.; Pinheiro, A.; Kaufmann, V.; Torres, E.; Piazza, A. G. Chemical and physical characteristics of a Haplic Cambisol of the Atlantic Rainforest Biome under different soil usages. Revista em Agronegócio e Meio Ambiente, v.13, p.1039-1066, 2020. https://doi.org/10.17765/2176-9168.2020v13n3p1039-1066.

He, Y.; Song, X.; Li, X.; Gao, Y.; Yang, J.; Chen, J.; Chen, J.; Cai, C. Spatial Properties of Soil Physical Quality Index S in Black Soil Croplands under Permanent Gully Erosion. Land, v.12, e1641, 2023. https://doi.org/10.3390/land12091641.

Hertel, D.; Moser, G.; Culmsee, H.; Erasmi, S.; Horna, V.; Schuldt, B.; Leuschner, Ch. Below-and above-ground biomass and net primary production in a paleotropical natural forest (Sulawesi, Indonesia) as compared to neotropical forests. Forest Ecology and Management, v.258, p.1904-1912, 2009. https://doi.org/10.1016/j.foreco.2009.07.019.

Jorge, L. A. C.; Silva, D. J. C. B. 2010. Safira: User manual. https://www.embrapa.br/busca-de-solucoes-tecnologicas/-/produto-servico/9702/safira---software-para-analise-de-fibras-e-raizes-por-imagem.

Klumb, G. B.; Veber, P. M.; Mello, L. B.; Rorneles, V. R.; Damé, R. de C. F.; Granda, C. F. A. T. Climatological water balance and Thornthwaite climatic classification for the municipality of Pelotas/RS. Brazilian Journal of Animal and Environmental Research, v.1, p.229-235, 2018.

Klute, A. Water retention: laboratory methods. In: Klute, A. (2nd Ed.) Methods of soil analysis. American Society of Agronomy, p.635–662, 1986.

Kumi, F.; Obour, P. B.; Arthur, E.; Moore, S. E.; Asare, P. A.; Asiedu, J.; Angnuureng, D. B.; Atiah, K.; Amoah, K. K.; Amponsah, S. K.; Dorvlo, S. Y.; Banafo, S.; Adu, M. O. Quantifying root-induced soil strength, measured as soil penetration resistance, from different crop plants and soil types. Soil and Tillage Research, v.233, e105811, 2023. https://doi.org/10.1016/j.still.2023.105811.

Laurenti, N.; Rodrigues, J.; Guimarães, E.; Pezzopane, J.; Bernardi, A. Spatial variability of soil and vegetation properties in integrated production systems. Brazilian Journal of Agricultural and Environmental Engineering, v.28, e280481, 2024. http://dx.doi.org/10.1590/1807-1929/agriambi.v25n1p3-9.

Leal, O. A.; Miguel, P.; Rodrigues, M. F.; Guimarães, R. M. L.; Pinto, F; K. S.; Silva, T. P.; Pinto, M. A. B.; Nachtigall, S. D.; Stumpf, L. First validation of the method Visual Evaluation of Soil Structure in coal mining area using a long-term field revegetation experiment as testbed. Soil and Tillage Research, v.246, e106347, 2025. https://doi.org/10.1016/j.still.2024.106347.

Lopes, V. S.; Cardoso, I. M.; Fernandes, O. R.; Rocha, G. C.; Simas, F. N. B.; Moura, W. M.; Santana, F. C.; Veloso, G. V.; Luz, J. M. R. The establishment of a secondary forest in a degraded pasture to improve hydraulic properties of the soil. Soil and Tillage Research, v.198, e104538, 2020. https://doi.org/10.1016/j.still.2019.104538.

Machado, B. D.; Magro, M.; Souza, D. S. de; Rufato, L.; Kretzschmar, A. A. Study on the growth and spatial distribution of the root system of different european pear cultivars on quince rootstock combinations. Revista Brasileira de Fruticultura, v.40, p.1-8, 2018. https://doi.org/10.1590/0100-29452018108.

Manea, A.; Mihail, D.; Gherghina, A.; Calciu, I.; Raducu, D.; Anghel, A. Physical quality evaluation of some soils from Doljcounty. Annals of the University of Craiova - Agriculture, Montanology, Cadastre Series. v.52, p.400-415, 2022. https://anale.agro-craiova.ro/index.php/aamc/article/view/1368/1287.

Minai, J. O.; Libohova, Z.; Schulze, D. G. Spatial prediction of soil properties for the Busia area, Kenya using legacy soil data. Geoderma Regional, v.25, e00366, 2021. https://doi.org/10.1016/j.geodrs.2021.e00366.

Ni, H.; Su, W. Spatial distribution of fine root traits in relation to soil properties and aggregate stability of intensively managed Moso bamboo (*Phyllostachys edulis*) plantations in subtropical China. Plant Soil, v.498, p.487-503, 2024. https://doi.org/10.1007/s11104-023-06449-x.

Panayiotopoulos, K. P.; Papadopoulou, C. P.; Hatjjioannidou, A. Compaction and penetration resistance of an Alfisol and Entisol and their influence on root growth of maize seedlings. Soil and Tillage Research, v.31, p.323–337, 1994. https://doi.org/10.1016/0167-1987(94)90039-6.

Peixoto, D. S.; Silva, B. M.; Oliveira, G. C.; Moreira, S. G.; Silva, F.; Curi, N. A soil compaction diagnosis method for occasional tillage recommendation under continuous no tillage system in Brazil. Soil & Tillage Research, v.194, e104307, 2019. https://doi.org/10.1016/j.still.2019.104307.

R Core Team. R: A language and Eenvironment for statistical domputing. R Foundation for Statistical Computing, Vienna, Austria, 2021.

Reichardt, K.; Timm, L. C. Soil, plant and atmosphere: concepts, processes and applications. Springer, Basel, 2020, 456p. https://link.springer.com/book/10.1007/978-3-030-19322-5.

Reichert, J. M.; Silva, V. R. da; Awe, G. O.; Wendroth, O. O.; Srinivasan, R. Defining tillage need for edible bean production under no-tillage: Classical and time series analyses. Soil and Tillage Research, v.202, e104671, 2020. https://doi.org/10.1016/j.still.2020.104671.

Reis, D. A.; Lima, C. L. R. de; Bamberg, A. L. Developing a soil physical quality index (SPQi) for lowlands under different deployment times of no-tillage. Scientia Agricola, v.76, p.157-164, 2019. https://doi.org/10.1590/1678-992X-2017-0196.

Santos, H. G. dos; Jacomine, P. K. T.; Anjos, L. H. C. dos; Oliveira, V. Á. de; Lumbreras, J. F.; Coelho, M. R.; Almeida, J. A. de; Araújo filho, José Coelho de; Oliveira, J. B. de; Cunha, T. J. F. Sistema Brasileiro de Classificação de Solos. 6. ed., rev. e ampl. Brasília, DF: Embrapa, 2025. https://www.embrapa.br/busca-de-publicacoes/-/publicacao/1176834/sistema-brasileiro-de-classificacao-de-solos.

Satriani, A.; Belviso, C.; Lovelli,S.; Prima, S.; Coppola, A.; Hassan, S. B. M.; Rivelli, A. R.; Comegna, A. Impact of a synthetic zeolite mixed with soils of different pedological characteristics on soil physical quality índices. Geoderma, v.451, e117084, 2024. https://doi.org/10.1016/j.geoderma.2024.117084.

Silva, T. P.; Centeno, L. N.; Lima, C. L R. de; Nunes, M. C. M.; Holthusen, D.; Timm, L. C. Investigating spatial relationships of soil friability and driving factors through co-regionalization with state-space analysis in a subtropical watershed. Soil and Tillage Research, v.212, e105028, 2021. https://10.1016/j.still.2021.105028.

Soares, M. F.; Centeno, L. N.; Timm, L. C.; Mello, C. R.; Kaiser, D. R.; Beskow, S. Identifying covariates to assess the spatial variability of saturated soil hydraulic conductivity using robust cokriging at the watershed scale. Journal of Soil Science and Plant Nutrition, v.20, p.1491-1502, 2020. https://doi.org/10.1007/s42729-020-00228-8.

Soil Survey Staff. Keys to Soil Taxonomy. 13.ed. USDA - Natural Resources Conservation Service, 2022. 401p. https://www.nrcs.usda.gov/resources/guides-and-instructions/keys-to-soiltaxonomy.

Teixeira, P. C.; Donagemma, G. K.; Fontana, A.; Teixeira, W. G. Manual de métodos de análise de solo. 3. ed. rev. e ampl. Brasília, DF: Embrapa, 2017. 574p.

Timm, L. C.; Pires, L. F.; Roveratti, R.; Arthur, R. C. J.; Reichardt, K.; Oilveira, J. C. M.; Bacchi, O. O. S. Field spatial and temporal patterns of soil water content and bulk density changes. Scientia Agricola, v.63, p.55-64, 2006. https://doi.org/10.1590/S0103-90162006000100009.

Vasconcelos, A. C. M.; Casagrande, A. A.; Perecin, D.; Jorge, L. A. C.; Landell, M. G. A. Avaliação do sistema radicular da cana-de-açúcar por diferentes métodos. Revista Brasileira de Ciência do Solo, v.27, p.849-858, 2003. https://doi.org/10.1590/S0100-06832003000500009.

Walkley, A.; Black, I. A. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Science, v.37, p.29-38, 1934. https://journals.lww.com/soilsci/citation/1934/01000/an_examination_of_the_degtjareff_method_for.3.aspx.

Wang, Y. Q.; Shao, M. A. Spatial variability of soil physical properties in a region of the Loess Plateau of pr China subject to wind and water erosion: spatial variability of soil physical properties. Land Degradation & Development, v.24, p.296-304, 2013. https://doi.org/10.1002/ldr.1128.

Wilding, L. P.; Drees, L. R. Spatial variability and pedology. In: Wilding, L. P.; Smeck, N. E; Hall, G. F. (2nd ed.) Pedogenesis and soil taxonomy: 1. concepts and soil analysis. American Society of Agronomy: Madison, 1983. p.83-116.

Zanchin, M.; Moura, M. M.; Nunes, M. C. M. N.; Beskow, S.; Miguel, P.; Lima, C. L. R.; Bressiani, D. A. B. Soil loss estimated by means of the RUSLE model in a subtropical climate watershed. Revista Brasileira de Ciência do Solo, v.45, e0210050, 2021b. https://doi.org/10.36783/18069657rbcs20210050.

Zanchin, M.; Moura, M. M.; Nunes, M. C. M.; Tuchtenhagen, I. K.; Lima, C. L. R. Assessment of soil loss susceptibility in Santa Rita watershed in southern Brazil. Engenharia Agrícola, Jaboticabal, v.41, p.485-491, 2021a. https://doi.org/10.1590/1809-4430-Eng.Agric.v41n4p485-495/2021.