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Spatial Variability and Correlation between Soil Physical Properties under No-Tillage with and without Agricultural Terraces

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HIGHLIGHTS

- Macro has mean and Ks has high variability.
- The agricultural terraces can positively influence the behavior of Ks.
- Ks and Macro have a significant positive correlation.
- The absence of agricultural terraces can provide a reduction of Ks with soil depth.

Abstract: The terracing is important for erosion processes control in agricultural areas. However, agricultural terraces are being removed from the production areas under no-tillage systems. There are still uncertainties about the terracing effects on the soil saturated hydraulic conductivity (Ks) and macroporosity (Macro), which represent the functionality of the system. We aimed to evaluate the magnitude and spatial distribution of Ks and Macro and the correlation between these soil properties in two paired megaplots, of 1.923 ha, one with terraces (T) and another without terraces (WT). Ks and Macro were determined at 0.00-0.10 m, 0.10-0.20 m, 0.20-0.30 m, and 0.30-0.40 m soil layers and submitted to descriptive statistical, geostatistics, and Spearman correlation analysis. Ks was highest in the 0.00-0.20 m and lowest in the 0.20-0.40 m layers in T. In WT, Ks was highest in the 0.00-0.10 m and lowest in the 0.10-0.40 m layers. However, the Macro was highest in the 0.00-0.10 m and lowest in the 0.10-0.40 m layers in both megaplots. Ks and Macro had a positive correlation in both megaplots. The spatial distribution of Ks and Macro had a positive correlation, with regions with higher Ks coinciding with regions with higher Macro in both megaplots. The spatial distribution of Ks and Macro in WT did not have a clear trend, while in T there was a slight stratification in strips interspersed with higher and lower Ks and Macro. These initial trends are not conclusive considering the short term between terraces removal and Ks and Macro evaluation.

Keywords: soil saturated hydraulic conductivity; macroporosity; correlation between soil properties; geostatistics.

INTRODUCTION

The sustainability and functionality of production systems depend on the structural quality of the soil, which must be sufficient to allow air and water flows, to resist factors and processes that attempt to deform the soil, and to allow the growth and development of edaphic and plant organisms. Soil saturated hydraulic conductivity (Ks) and soil macroporosity (Macro) are soil physical properties used to describe soil structural quality and water and air flow capacity.

The Ks represents the ease with which water moves in the soil. This soil property is used to describe processes and as input data in distributed hydrologic models [1,2,3] to predict hydrological and erosion processes at different scales of analysis, from soil profile to the watershed scale. Therefore, it is important that Ks be properly quantified in the short and long term and also spatially distributed.

The Ks depends on intrinsic soil factors such as texture and geometry of the pore space [4,5,6]. The volume and continuity of the large pores (macropores) [4,5] are the main physical properties of the soil that have a direct influence on the Ks behavior. The area of the largest pores can explain about 80% of the variability in the soil saturated hydraulic conductivity [7]. Therefore, macroporosity can be used as a proxy to estimate the spatial variability of Ks [6] and consequently, the runoff, because variations in soil macroporosity variations are themselves sufficient to explain Ks variations over a multiscale and site-scale range [6]. In addition, factors external to the soil, such as topography [1,8], soil management [9], and scale of analysis [10] also influence Ks, as they affect the geometry of the pore space. These integrated factors provide high spatial variability of Ks [4,5,6], which can reach more than two orders of magnitude, ranging from large scales such as watersheds to small areas such as areas of 0.1 km^2 [10,11].

The soil tillage and management system, the adoption of complementary water and soil conservation practices, and changes in soil and land use management are factors that provide high spatial variability of Ks in an area and in long-term because the pore size distribution is very sensitive to these practices and their influence on Ks. Soil tillage, land use and management, and conservation practices influence the distribution, geometry [12], and functionality of the porous system [13]. These practices, if done improperly, can degrade and reduce soil quality and, as a consequence, reduce crop productivity and increase soil degradation processes, such as compaction and soil erosion.

Conventional tillage, which was prevalent in agricultural production areas until the 1970s and 1980s [14], relied on intensive tillage [15]. However, this tillage provides a short duration of the benefits obtained by plowing, and negative effects such as the low water infiltration into the soil caused by the formation of a compacted layer in the subsoil and through the effects of water erosion [16,17]. Terracing was a complementary soil conservation practice often used to reduce soil and water losses in areas under conventional tillage [15]. Terraces are mechanical barriers built transversally on the slope to reduce the length of the ramp and the velocity and volume of runoff that results from low infiltration of water into the soil. Agricultural terraces are efficient at controlling soil losses by runoff [18,19], but they are not enough to control the whole negative effects of conventional tillage, which has led to the adoption of more efficient systems and techniques to reduce soil and water losses, such as the no-tillage system [20]. The no-tillage system, when properly conducted, reduces soil erosion [21,22], sediment yield, and water loss from the landscape and watersheds [17,23,24]. The use of this system in agricultural areas can reduce soil losses by up to five times compared to the conventional system [25].

The no-tillage system also promotes soil disturbance reduction [16,26], maintenance of residues on the soil surface [16], and aggregate soil stabilization by increasing soil organic matter [26], which results in improved soil physical-mechanical soil quality and protection against compaction [21,22] and improved soil protection [27], by increasing macroporosity and pore connectivity [28]. Consequently, water infiltration into the soil and in the soil saturated hydraulic conductivity increase.

This improvement in soil quality led some rural producers to understand that direct seeding alone would be enough to prevent soil erosion and runoff [29,30], which led to the reduction or elimination of complementary conservation practices [29,30]. As a result, several farmers have removed totally or partially the agricultural terraces from their croplands. This practice has gradually increased, justified by the increase in area for cultivation and the facilitation of mechanized operations in crop production [31], such as seeding, agrochemical application, and harvesting.

However, agricultural soils cultivated under no-tillage often have a higher degree of compaction [32], which is associated with a reduction in soil microporosity [33], in soil saturated hydraulic conductivity [34], and soil water storage [35] and infiltration capacity into the soil [36]. In addition to these negative conditions for soil physical properties and water, there is been an increase in runoff, and soil, water, and nutrient losses due to erosion [37] which can pollute and silt up watercourses [38], with periods of water stress due to the lower amount of water infiltrated and stored in the soil [34], and productivity losses [36]. This soil degradation in areas under no-tillage is intensified mainly by the intensive traffic of machinery, generally under inadequate soil moisture conditions, and due to the low coverage of the soil with residues provided by the low addition of phytomass [36,39].

The runoff, even in areas under no-tillage, decreases the soil water infiltration capacity due to surface crusting caused by the impact of raindrops that cause soil disaggregation by transferring kinetic energy and forming the seal and surface crust [40]. Individualized particles are transported with water into the pores of the soil during percolation and cause clogging and discontinuity of the pores, mainly the macropores. These changes in soil structure, mainly in macroporosity, caused by the evolution and dynamics of soil management systems and the adoption of complementary conservation practices, such as terracing, coincide with the changes and structural consolidation of the soil that affect the water movement into the soil.

Terracing in areas under no-tillage is efficient in reducing runoff [41] and soil losses [42]. However, information is still lacking on the effects of the presence or absence of agricultural terraces in no-tillage areas on the behavior and correlation between macroporosity and hydraulic conductivity of saturated soil and on the spatial distribution of these properties, although the relationship between Ks and soil macroporosity is known [4,5,6].

Knowledge of the effects of agricultural terraces on these soil physical and water properties can be a critical factor in decision-making about maintaining terraces in no-tillage areas, not only to control runoff and erosion but also to improve structural quality and air and water fluxes in the soil, which can increase crop productivity. Therefore, our objective was to evaluate the magnitude and spatial distribution of hydraulic conductivity in saturated soil and soil macroporosity in areas with and without agricultural terraces and to investigate the correlation between these soil properties.

MATERIAL AND METHODS

The study was performed in two megaplots, one where the terraces were maintained in the area (with agricultural terraces-T) and the other where the terraces were removed (without agricultural terraces-WT). The megaplots delimitation and removal of terraces from WT were performed in May 2019. The megaplots are located at the Federal University of Technology - Paraná, Campus Dois Vizinhos (UTFPR -DV), between the geographic coordinates 25º 42' South latitude and 53º 06' West longitude, at an elevation of 509 m.

The climate in the region is mesothermal humid subtropical (Cfa) with no defined dry season, according to the Köppen climate classification [43]. The mean temperature of the warmest month is above 22 °C and the coldest month is below 18 °C [43]. The annual rainfall ranges between 1800 and 2200 mm, with an annual mean of 2011 mm [44]. Rainfall is well distributed throughout the year, with October and January being the wettest months and July and August the months with the least rainfall [44].

The regional geology is characterized by the presence of basaltic rocks from the Serra Geral Formation, formed from basaltic lava flows that occur in the Third Paraná Plateau [45]. The soil in the study area is classified as Nitosolo Vermelho [46] according to the Brazilian Soil Classification System [47] and as Nitisols according to the World Reference Base for Soil Resources system [48], with an mean particle size distribution in the 0.00-0.40 m layer of 20.0 g kg^{-1} of sand, 294.2 g kg^{-1} of silt and 685.8 g kg^{-1} of clay, and very clay texture. The predominant relief is flat to undulating, with a slope of less than 10% in most of the region.

The megaplot with terraces (T; 1.923 ha) has 203.60 m of length and an mean slope of 8.98%, while the megaplot without terraces (WT; 1.923 ha) has 206.50 m of length and an mean slope of 8.62%.

Soil sampling was performed in October 2020. Undisturbed soil samples were taken from 0.00-0.10 m, 0.10-0.20 m, 0.20-0.30 m and 0.30-0.40 m soil layers in 32 equidistant points 24 m in each megaplot, by using metal cylinders (5 x 5 cm).

Soil samples were prepared and metal cylinders of the same diameter were fixed over the samples with adhesive tape. The samples were saturated for 48 hours and subjected to analysis of the Ks in a constant head permeameter [49]. The volume of water percolated in each sample was collected at 10-minute intervals and quantified for at least three hours until stability of percolating volume was achieved for three consecutive measurements. When this stability was achieved, these three readings of the volume of water percolated composed repetitions for each soil sample. Subsequently, samples were then saturated again for 48 hours, weighed, and kept in a sand column at a water tension of 6 kPa for 72 hours. Then the samples were weighed and kept in an oven at 105 °C until they reached a constant weight.

The total porosity consists of the volume of water retained at saturation. The volume of micropores was determined considering the volume of water retained in the soil at a water tension of 6 kPa. The volume of macropores (Macro) was determined by the difference between the total porosity and the microporosity [49].

Descriptive statistics

Measures of position and dispersion of the data were calculated to obtain the mean, median, variance, standard deviation, asymmetry, kurtosis, extreme values and coefficient of variation of the soil saturated hydraulic conductivity and the macroporosity. The variability of soil saturated hydraulic conductivity and the macroporosity was classified based on the coefficient of variation (CV) as low (CV < 12%), mean (12% < CV < 60%), and high (CV > 60%), as suggested by Warrick and Nielsen [50].

The Shapiro-Wilk test, at a 0.05 significance level, was applied to evaluate the frequency distribution and normality of the Ks and the Macro. The presence of outliers was checked using box-plot graphs; however, the outliers were not removed to perform the aforementioned procedures due to the high variability of the soil saturated hydraulic conductivity. Subsequently, the correlation between Ks and Macro was evaluated using the Spearman's bivariate correlation test, for all soil layers of megaplots with terraces (T) and without terraces (WT).

Geostatistics

The spatial distribution of soil saturated hydraulic conductivity and macroporosity was evaluated using geostatistics. Firstly, the spatial dependence of the soil properties was analyzed using the classical semivariogram estimator described by Matheron [51], using the equation that represents the semivariance of the data γ (h) as a function of the distance that separates them (h) (Equation 1).

$$\gamma(h) = \frac{1}{2N(h)} \sum_{N(h)} [z(x_i + h) - z(x_i)]^2 \quad (1)$$

Where: γ (h) is the semivariance, z is the variable under study, z (x_i) and z (x_i + h) are pairs of values measured in the sampled geographical position separated by a distance h, and N (h) is the number of pairs with the lag distance h between them.

The experimental semivariogram was fitted by the theoretical semivariograms of the spherical, exponential, and Gaussian models, including the following parameters: Range (a), sill (C = C_0 + C_1), the component with spatial structure (C_1), and nugget effect (C_0). The choice of the best theoretical model fitted to the experimental semivariogram was made by cross-validation, in which the values of the root mean square error (RMSE) and the coefficient of determination (r^2) are obtained. Subsequently, interpolations were performed by ordinary kriging and then spatial distribution maps were generated, when properties had spatial dependence in each sampling point. Finally, the degree of spatial dependence (DSD) was determined according to the criteria proposed by Cambardella and coauthors [52], where the DSD is the percentage ratio of the nugget effect (C_0) in relation to the sill (C), i.e., $C_0/C_1 + C_0$. The DSD is strong when the percent values ≤ 25%, moderate between 25% and 75%, and weak when between 75% and 100%. DSD values equal to 100% are randomly distributed and considered independent.

Data analysis and generation of spatial distribution maps were performed using the R software [53].

The spatial dependence of Ks for the surface soil layer (0.00-0.10 m) in the CT had a better fit with the linear model, while the other soil layers (0.10-0.40 m) had a pure nugget effect. In ST, the Ks spatial dependence model for the 0.00-0.10 m and 0.30-0.40 m soil layers was the linear model and the Gaussian model, respectively, and the 0.10-0.20 m and 0.20-0.30 m had pure nugget effect. The spatial dependence of Macro for the surface soil layer (0.00-0.10 m) in CT had a better fit with the spherical model and the other soil layers (0.10-0.40 m) had a pure nugget effect. The spatial dependence of Macro on ST in the 0.00-0.10 m soil layer was linear and the other layers had a pure nugget effect.

RESULTS

Mean Ks was higher in the surface layer and decreased with increasing soil depth in T and WT. Ks was numerically higher in T compared to WT in most soil layers, except in the 0.30-0.40 m layer (Table 1). The variability of Ks, represented by CV, also increased with increasing soil depth. Ks had lower CV in surface soil layers (0.00-0.20 m) and higher CV in deeper soil layers (0.30-0.40 m) in T compared to WT (Table 1). In T, the mean Ks in the surface soil layer (0.00-0.10 m) was 4.870 cm h^{-1} (CV = 64.44%), 2.077 cm h^{-1} (CV

= 66.01%) in the 0.10-0.20 m soil layer, 1.313 cm h^{-1} (CV = 104.49%) in the 0.20-0.30 m soil layer and 1.027 cm h^{-1} (CV = 148.69%) in the 0.30-0.40 m soil layer. In WT, the mean Ks was 4.499 cm h^{-1} (CV = 73.48%) in the 0.00-0.10 m soil layer, 1.675 cm h^{-1} (CV = 73.49%) in the 0.10-0.20 m soil layer, 1.277 cm h^{-1} (CV = 95.62%) in the 0.20-0.30 m soil layer and 1.389 cm h^{-1} (CV = 109.50%) in the 0.30-0.40 m soil layer (Table 1).

The spatial distribution of Ks had a slight stratification in the 0.00-0.10 m soil layer in the T, with strips of smaller Ks in the middle slope and in the extreme portions of the relief, as in the highest portion of the relief located further south and in the lower portion of the relief, located further north, and strips with higher Ks in intermediate positions and interspersed with the previous ones (Figure 1). The spatial distribution of Ks in the WT did not have a strip stratification in the surface soil layer (0.00-0.10 m), however, Ks was greater in the diagonal direction of the megaplot, being greater in a part of the top of the landscape and decreasing diagonally along the slope. In this layer, the smallest Ks occurred in the lowest position of the landscape, located further north. In the 0.20-0.30 m soil layer of the WT, Ks was higher in a few points and lower mainly in the middle third of the WT in several points. In the deepest soil layer (0.30-0.40 m), the highest Ks occurred in the upper and lower part of the slope, while the lowest Ks occurred in the middle third of the megaplot (Figure 1).

The mean Macro was higher in the surface soil layer (0.00-0.10 m) and decreased with increasing soil depth in the T. In WT, the Macro was higher in the surface soil layer but did not tend to decrease with increasing soil depth. Macro was numerically higher in WT compared to T in most layers, except in the 0.10-0.20 m soil layer (Table 1). Macro variability, represented by CV, did not tend to increase or decrease with increasing soil depth, however, CV had a lower magnitude when compared to Ks (Table 1).

Mean Macro was greater than 0.10 cm^3 cm^{-3} in all soil layers, in T and WT (Table 1). In T, the mean Macro was 0.134 cm^3 cm^{-3} (CV = 29.85%) in the surface soil layer (0.00-0.10 m). The Macro was 0.118 cm^3 cm^{-3} (CV = 23.73%) in the 0.10-0.20 m soil layer, 0.113 cm^3 cm^{-3} (CV = 31.86%) in the 0.20-0.30 m and 0.111 cm^3 cm^{-3} (CV = 29.73%) in the 0.30-0.40 m soil layer. In WT, the mean Macro was 0.136 cm^3 cm^{-3} (CV = 33.09%) in the 0.00-0.10 m soil layer. The mean Macro was 0.116 cm^3 cm^{-3} (CV = 23.28%) in the 0.10-0.20 m soil layer, 0.119 cm^3 cm^{-3} (CV = 23.53%) in the 0.20-0.30 m soil layer and 0.119 cm^3 cm^{-3} (CV = 20.17%) in the 0.30-0.40 m soil layer. The stratification of Macro in intercalated strips was also slight and coincides with the Ks stratification in the surface soil layer (0.00-0.10 m) in T (Figure 2). The greatest Ks occur at locations that coincide with the greatest Macro. In the WT, the spatial distribution of the Macro did not show a stratification in strip in the surface soil layer, however, the Macro was greater in the diagonal direction of the megaplot (Figure 2). In both megaplots, the greatest Ks occur at locations that coincide with the greatest Macro. This visual relationship observed in the spatial distribution maps of the Ks and Macro was confirmed by the linear correlation analysis between these variables (Table 2).

The correlation between Ks and Macro was significant in 0.00-0.10 m, 0.10-0.20 m and 0.20-0.30 m soil layers in T and WT. Ks and Macro were not significantly correlated in the 0.30-0.40 m soil layer. Spearman's correlation coefficients between Ks and Macro were higher in T compared to WT (Table 2).

Table 1. Descriptive statistics for soil saturated hydraulic conductivity and macroporosity in the megaplots with terraces (T) and without terraces (WT), in Dois Vizinhos municipality, in the southwestern region of Paraná State, Southern Brazil.

Soil depth (m)	N	Mean	Median	Variance	Standard deviation	Skewness	Kurtosis	Minimum	Maximum	CV (%)	W	p-value
Soil saturated hydraulic conductivity (cm h^{-1})												
WT												
0.00-0.10	32	4.499	3.710	10.932	3.306	0.889	0.081	0.029	12.665	73.483	0.918	0.018
0.10-0.20	32	1.675	1.699	1.516	1.231	0.639	0.413	0.000	5.339	73.493	0.942	0.085
0.20-0.30	32	1.277	1.092	1.490	1.221	1.184	1.777	0.000	5.412	95.615	0.866	0.001
0.30-0.40	32	1.389	0.689	2.312	1.521	0.883	-0.412	0.018	5.388	109.503	0.834	< 0.001
T												
0.00-0.10	32	4.870	3.793	9.848	3.138	1.468	1.285	1.449	13.895	64.435	0.809	< 0.001
0.10-0.20	32	2.077	2.068	1.879	1.371	0.419	-0.228	0.047	5.598	66.009	0.959	0.256
0.20-0.30	32	1.313	0.974	1.882	1.372	1.139	0.682	0.000	5.155	104.494	0.858	0.001
0.30-0.40	32	1.027	0.297	2.331	1.527	1.826	2.214	0.026	5.768	148.685	0.676	< 0.001
Macroporosity (cm^3 cm^{-3})												
WT												
0.00-0.10	32	0.136	0.133	0.002	0.045	0.144	0.473	0.024	0.250	33.088	0.983	0.890
0.10-0.20	32	0.116	0.108	0.001	0.027	0.384	-0.881	0.069	0.171	23.276	0.961	0.284
0.20-0.30	32	0.119	0.119	0.001	0.028	0.703	1.128	0.067	0.207	23.529	0.957	0.233
0.30-0.40	32	0.119	0.119	0.001	0.024	0.451	-0.759	0.081	0.177	20.168	0.960	0.277
T												
0.00-0.10	32	0.134	0.121	0.002	0.040	0.732	-0.331	0.072	0.226	29.851	0.934	0.050
0.10-0.20	32	0.118	0.114	0.001	0.028	0.497	-0.643	0.072	0.179	23.729	0.956	0.219
0.20-0.30	32	0.113	0.109	0.001	0.036	0.260	-0.314	0.045	0.197	31.858	0.980	0.809
0.30-0.40	32	0.111	0.107	0.001	0.033	0.100	-1.223	0.054	0.168	29.730	0.958	0.247

[1]N: number of observations; CV: coefficient of variation; W: Shapiro-Wilk test.

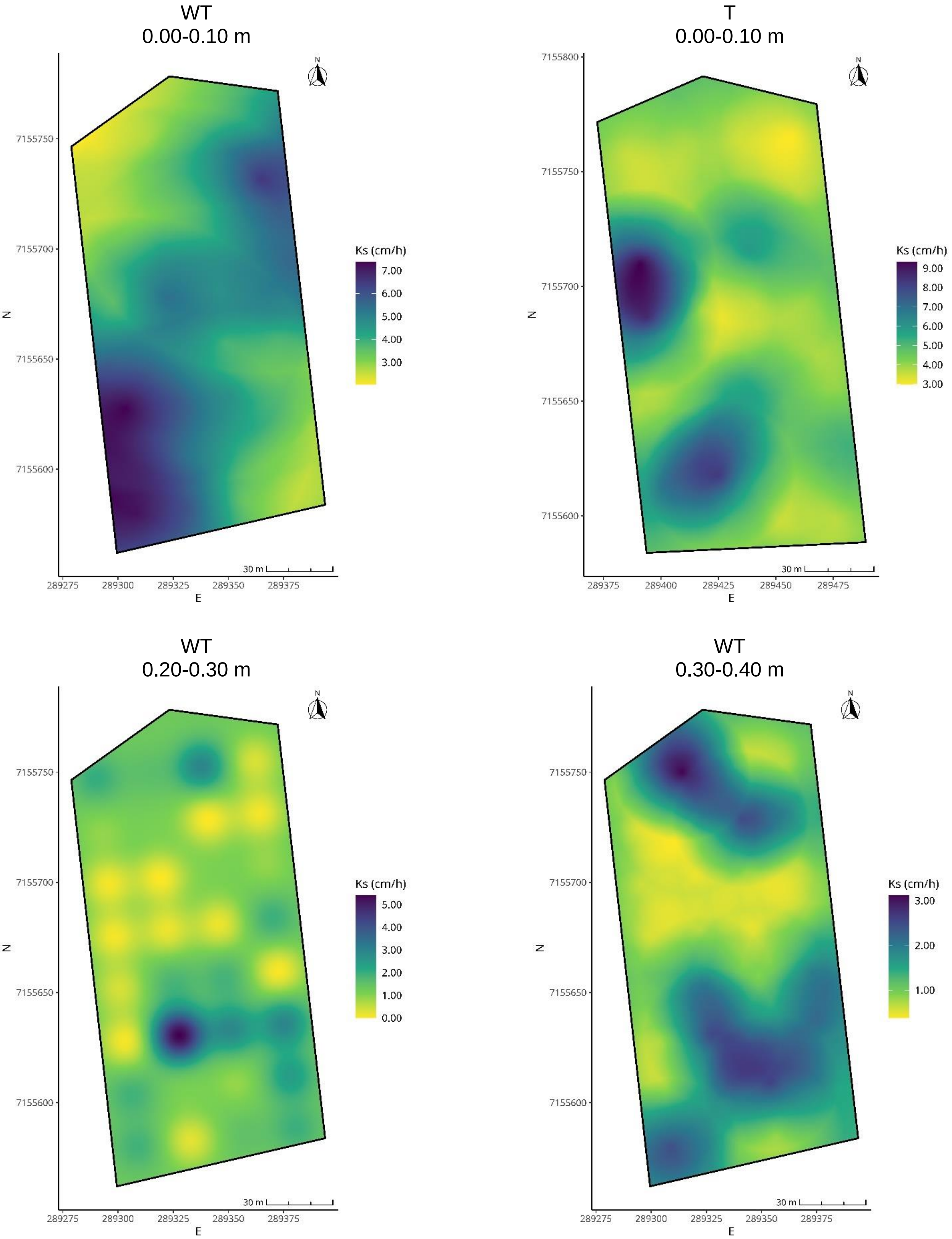

Figure 1. Spatial distribution of soil saturated hydraulic conductivity (Ks) in different soil layers in the megaplots with terraces (T) and without terraces (WT), in Dois Vizinhos municipality, in the southwestern region of Paraná State, Southern Brazil.

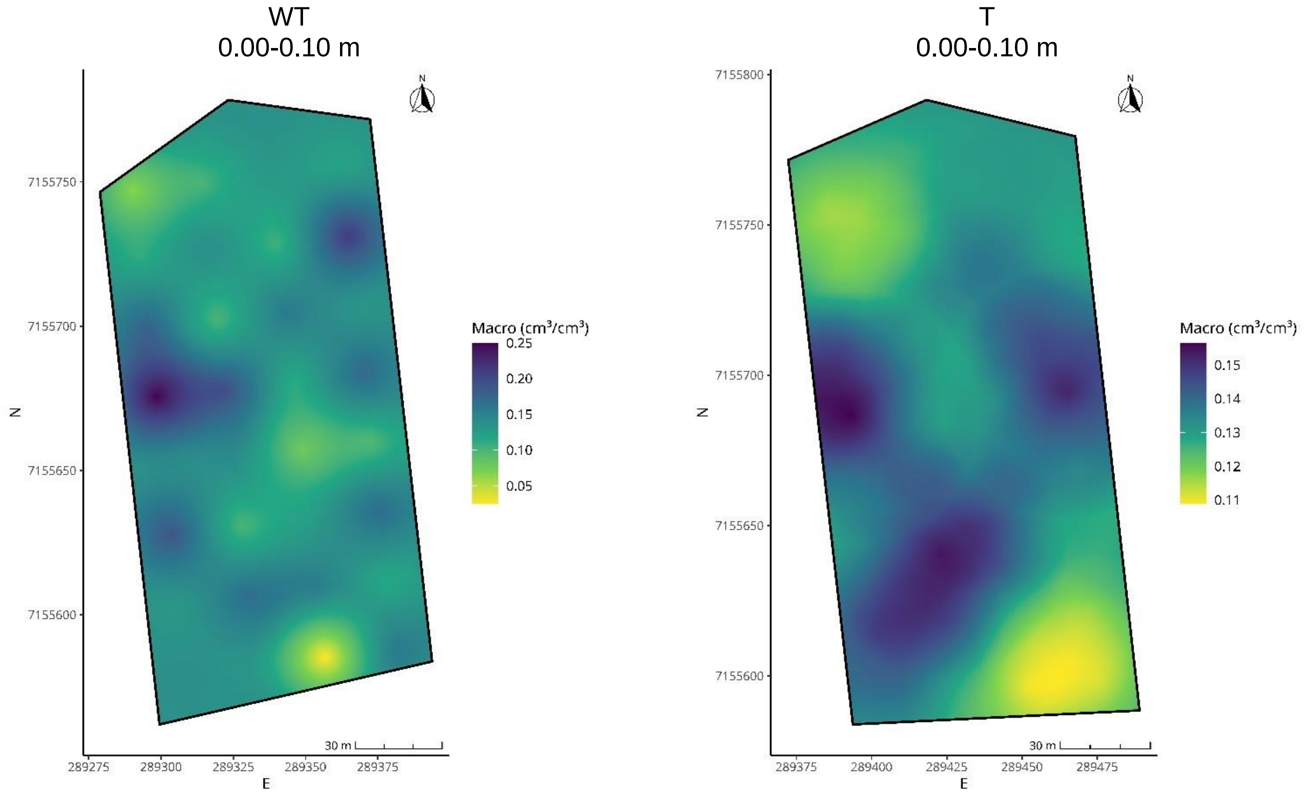

Figure 2. Spatial distribution of macroporosity (Macro) in different soil layers in the megaplots with terraces (T) and without terraces (WT), in Dois Vizinhos municipality, in the southwestern region of Paraná State, Southern Brazil.

Table 2. Spearman correlation coefficient (*ρ*) between soil saturated hydraulic conductivity and macroporosity in the megaplots with terraces (T) and without terraces (WT), in Dois Vizinhos municipality, in the southwestern region of Paraná State, Southern Brazil.

Soil layer (m)	T		WT	
	ρ	p-value	*ρ*	p-value
0.00-0.10	0.664	< 0.001	0.448	0.011
0.10-0.20	0.587	< 0.001	0.456	0.009
0.20-0.30	0.617	< 0.001	0.441	0.012
0.30-0.40	0.279	0.122	0.273	0.131

DISCUSSION

Magnitude and behavior of the Ks and Macro

Ks has a positive correlation with Macro (0.00-0.30 m) in T and WT. This correlation was expected since macropores favor preferential water flow and, as a consequence, higher Macro implies in higher Ks [6,54]. However, the correlation coefficient and significance were lower in WT compared to T, since these soil properties can be influenced not only by soil structural conditions, but also by landscape conditions and the effects of erosion processes, such as clogging and discontinuity of soil pores.

The Macro, in T and WT, was greater than 0.10 cm^3 cm^{-3}, which is considered a critical limit for crop development [55], since air-filled porosities < 10% are characteristic of deficient aeration [56,57]. However, the Macro was between 10-25% and in this range there may be a limitation to gas exchange under certain conditions, since an air-fílled porosity of 25% provides good aeration [56,57].

Macro behavior was similar between the megaplots, with the highest Macro in the surface soil layer (0.00-0.10 m) and the lowest in the subsurface layers (0.10-0.40 m) in both megaplots. This behavior is expected, since macroporosity tends to be lower in subsurface soil layers in areas under no-tillage due to the tendency for greater compaction in this planting system [58].

Ks ranged from moderate to moderately slow [59] in both megaplots. Ks in the surface layers (0.00-0.20 m) of the terraced megaplot (T) was moderate (2.00-6.30 cm h^{-1}; [59]) and moderately slow (0.51-2.00 cm h^{-1}; [59]) in deeper soil layers (0.20-0.40 m). In the megaplot without terraces (WT), Ks was moderate (2.00-6.30 cm h^{-1}; [59]) only in the most surface soil layer (0.00-010 m) and moderately slow (0.51-2.00 cm h^{-1}; [59]) in soil layers of 0.10-0.40 m.

As there is a positive correlation between Macro and Ks, it was expected that the behavior and magnitude of these properties would be similar between WT and T megaplots in depth. However, this behavior was not observed, since the similarity in Macro behavior between T and WT megaplots, in depth, did not reflect the similarity in Ks. The difference in Ks behavior between the T and WT megaplots, with lower Ks at greater depths in the WT compared to the T, can be influenced by the erosive effect and runoff caused by the absence of terraces in the WT.

Even if the Macro is similar in pore volume, they can be discontinuous. Runoff and the impact of raindrops cause soil disaggregation by transferring kinetic energy [40]. Soil particles individualized with disaggregation are carried by runoff along the slope of the land, since there are no mechanical barriers to control it [50] and form the seal and surface crust [40]. In addition, these particles are also transported with surface water into the soil pores during percolation and cause pore clogging and discontinuity [60,61], which, consequently, provides a reduction in Ks, as observed in most layers of the WT, except in the surface layer, which has a greater influence of organic matter and roots.

The higher Ks in the surface layers of the T can indicate a positive effect of terraces on soil infiltration and water movement into the soil during rainfall events. The terraces provide reduction in the volume and velocity of runoff through the terraces [41]. As a consequence, the formation of seal and surface crust and clogging of pores are reduced in the areas with terraces. This implies that the terraced areas have high control and reduction in water losses by runoff [41] and also can improve the physical properties of the soil related to the functionality of the porous system, such as Ks.

The higher Ks in the surface layers may occurred due to the higher structural quality and more stable and continuous macropores, which favors the movement of water in the soil [4,5]. This soil quality condition is possibly provided by a greater concentration and action of the roots [62] and by the accumulation of organic matter on the surface [26].

Variability and spatial distribution of the Ks and Macro

The high variability of Ks, both in the megaplot with terraces (T) and in the megaplot without terraces (WT), is evidenced by the coefficient of variation of Ks, which was high (CV > 60%; [50]) for all layers of soil in the two megaplots. While Macro had a mean CV (12% < CV < 60%; [50]) in all layers of both megaplots (T and WT). This lower variability of Macro, with a mean coefficient of variation, compared to Ks was also observed in other studies (CV = 16%, [63]; CV > 20%, [64]; CV up to 37%, [65,66]).

Ks has high variability [5,6,67] represented by the high CV (CV = 110%, [68]; CV up to 114%, [69]) in clayey soils like those in this study. This high variability occurs due to the sensitivity of Ks to the structural dynamics of the soil, so small changes can generate large changes in its behavior [70].

The stratification into strips interspersed with higher and lower Ks and Macro in the surface layer (0.00-0.10 m) in the T may be the result of the presence of terraces since these structures reduce the velocity and volume of runoff and may have provided the deposition of eroded particles between agricultural terraces and transported to the subsequent terraces [71]. The deposition of particles next to the terrace dyke can form the seal and the surface crust [40] and the clogging and discontinuity of the soil pores [72] in these places, which decreases the Ks [5] and may have favored the formation of strips with different magnitudes of Ks. However, these results indicate an initial trend and are not conclusive considering the short term between the removal of agricultural terraces and the evaluation of Ks and Macro.

The Ks and Macro in the surface layer (0.00-0.10 m) of the WT are lower in the border areas of the megaplot, possibly due to the greater machine traffic during sowing, harvesting, and pesticide applications [73], which may have intensified soil compaction in these locations and reduced macroporosity and soil permeability [58,74]. The largest Ks diagonally along the slope and in the central portion of the WT, however, were still smaller than the Ks in the T. The lower Ks in the lowest position of the landscape may be due to surface sealing and pore clogging by particles that come of the soil, the impact of raindrops and runoff, which has greater energy for disaggregation, and the deposition of particles in these locations, since there are no mechanical barriers to control runoff along the slope of the land [60].

CONCLUSION

The soil saturated hydraulic conductivity (Ks) remains higher at greater depth in terraced areas compared to non-terraced areas. The Ks is considered moderate up to 0.20 m depth and moderately slow from 0.20 to 0.40 m in areas with terraces, while in areas without terraces, Ks is moderate only in the most surface soil layer, up to 0.10 m in depth, and moderately slow from 0.10 to 0.40 m in areas without terraces.

Soil macroporosity (Macro) had similar behavior in areas with and without terraces, with greater magnitude up to 0.10 m depth and smaller magnitude from 0.10 to 0.40 m. Macro was greater than 0.10 cm^3 cm^{-3}, which is considered a critical limit for crop development, in all soil layers.

The Ks variability is high, as evidenced by the coefficient of variation (CV) > 60%, while the Macro variability is mean CV (12% < CV < 60%).

The spatial distribution of Ks and Macro highlighted the variability of these properties, mainly of the Ks. These results indicate a trend of the influence of agricultural terraces on Ks and Macro in areas under no-tillage system, which provided interspersed strips of larger and smaller Ks and Macro, in the surface soil layer due to runoff and erosion control between terraces, which as low observed in areas without terraces. However, these results indicate an initial trend and are not conclusive considering the short term between the removal of terraces and the evaluation of Ks and Macro.

Ks and Macro had a significant positive correlation in soil layers up to 0.30 m deep in both areas with and without terraces, however this correlation had a higher level of significance in areas with terraces. The spatial distribution of Ks and Macro had a positive correlation, with regions with higher Ks coinciding with regions with higher Macro in both megaplots.

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