CIENCIA DEL SUELO

PROPIEDADES FÍSICA E HIDRÁULICAS DEL SUELO EN LA REGIÓN SUBTROPICAL DE BRASIL

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ABSTRACT

Agricultural systems can alter the soil physical and hydraulic properties, and consequently its quality. We aimed to determine and associate the physical and hydraulic properties of four soil types under no-tillage system in the Subtropical region of Brazil, as well as to create a data set available to be explored by further studies. Disturbed and undisturbed soil samples were collected from three layers: 0.0 - 0.10 m; 0.10 - 0.25 m; and 0.25 - 0.40 m at six localities in the Paraná and São Paulo States. Soil texture, soil bulk density and particle density, porosity (total, macro and micro), volumetric water content (permanent wilting point and field capacity), available water capacity and saturated hydraulic conductivity were determined. The average soil bulk density was within 1000 kg m^{-3} to 1400 kg m^{-3}, which is considered optimum for the respective soil textures. The average total porosity (between 0.47 m^3 m^{-3} and 0.63 m^3 m^{-3}) was close to an optimal condition for annual crop development under no-tillage system. The proportion between micro and macropores was approximately 2:1. The average values of soil available water capacity ranged from 48 mm to 60 mm. The average for the saturated hydraulic conductivity was classified as “moderate”. The management adopted for more than 20 years in the studied areas did not bring about critical values for the eleven physical and hydraulic soil properties examined, when compared to acceptable ranges verified in literature.

Key words: texture, bulk and particle density, porosity, saturated hydraulic conductivity.

SOIL PHYSICAL AND HYDRAULIC PROPERTIES OF BRAZIL

RESUMEN

Los sistemas agrícolas pueden alterar las propiedades física e hidráulicas del suelo y, en consecuencia, su calidad. Nuestro objetivo fue determinar y asociar las propiedades física e hidráulicas de cuatro tipos de suelo bajo un sistema de siembra directa sobre rastrojo, localizados en la región subtropical de Brasil, así como crear un conjunto de datos disponibles que pueden ser utilizados en estudios posteriores. Fueron recolectadas muestras de suelo alteradas y inalteradas en tres camadas: 0,0 - 0,10 m; 0,10 - 0,25 m; y 0,25 - 0,40 m en seis localidades de los estados de Paraná y São Paulo. Fueron determinados la textura del suelo, la densidad aparente y de las partículas del suelo, la porosidad (total, macro y micro), la humedad volumétrica del suelo (punto de marchitez permanente y capacidad de campo), la capacidad de agua disponible y la conductividad

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hidráulica saturada. El promedio de la densidad aparente del suelo está dentro de limites considerados óptimos (1000 kg m^{-3} y 1400 kg m^{-3}) de acuerdo con las clases texturales del suelo. El promedio de la porosidad total según los suelos estudiados (entre 0.47 m^3 m^{-3} y 0.63 m^3 m^{-3}) se mantuvo próxima a la condición ideal para el desarrollo anual de la cultura en sistema de siembra directa sobre rastrojo. La proporción entre micro y macroporos fue de aproximadamente 2:1. El promedio de la capacidad del agua disponible del suelo ha variado entre 48 mm y 60 mm. La conductividad hidráulica saturada promedio fue clasificada como "moderada". El manejo adoptado por más de 20 años en las áreas estudiadas no presentó alteración en las once propiedades físicas e hidráulicas del suelo, al compararlo con los límites normales establecidos en la literatura.

Palabras clave: Textura, Densidad aparente y de partículas, Porosidad, Conductividad hidráulica saturada.

INTRODUCTION

The consequences of management practices on soil physical quality directly affect crop development in the agricultural system. Thus, the knowledge of the impacts caused by cropping systems becomes essential. Some physical and hydraulic soil properties may help to understand how soil classes and management influence soil quality, reflecting the nutrient, water and root dynamics of the soil profile (Demattê *et al.*, 2017).

Tillage systems can directly affect soil attributes, influencing the physical quality and water availability for plants (Cassol *et al.*, 2017). The non-mobilization of soil and the accumulation of organic material cause significant changes in physical and hydraulic soil properties and may affect soil quality (Stone *et al.*, 2006).

Many soil attributes have great utility in crop planning and soil quality assessment. Although some authors say that soil bulk density (ρ_S) is not a useful indicator of soil quality (Logsdon & Karlen, 2004), this attribute may be modified by soil use and management, resulting in changes in soil function (Corstanje *et al.*, 2017; Caviglione, 2018). The alteration of ρ_S affects soil porosity and, consequently, the availability of water to plants as well as the productive capacity and soil quality. The assessment of moisture at field capacity (θ_{FC}) and at permanent wilting point (θ_{PWP}) and the available water capacity (*AWC*) of the soil allow quantifying the availability of water for agricultural crops. They can be used to monitor and to estimate soil water balance (Horne & Scotter, 2016) and, consequently, is valuable to assist in the decisions of management strategies. Tillage systems can alter pore distribution by size, also changing the soil water retention curve (*SWRC*) and its attributes (Reichardt & Timm, 2012; Cassol *et al.*, 2017).

The physical and hydraulic soil properties and the widespread data dissemination are important and critical for orienting soil management and broader soil quality studies. As commonly reported in literature, the use of no-tillage in place of tillage systems can alter pore distribution by size, also changing the soil water retention curve (SWRC). Other soil properties may also be altered as function of soil management but such information is not gathered together and interpreted in light of soil quality. Thus, we aimed to determine and associate physical and hydraulic soil properties under no-tillage systems in the Subtropical region of Brazil, as well as to raise data to be available for future studies.

MATERIALS AND METHODS

The study was carried out in Paraná and São Paulo States, covering part of the subtropical region of Brazil.

The soil samples were collected in experimental plots from the ABC Foundation (Fundação ABC, 2019), located in the cities of Arapoti-PR, Ponta Grossa-PR and Tibagi-PR, where the soils were classified as Oxisols; also at Castro-PR, in an Inceptisol; Itaberá-SP in an Alfisol; and at Socavão-PR in a Histosol (Soil Survey Staff, 2014). The soil classification was obtained from the 1:10,000 soil maps from a survey conducted by the ABC Foundation following the Brazilian Classification System, and the climate types were identified by Alvares *et al.* (2013) using the Köppen climate classification (**Figure 1**).

Examined plots have 50 x 100 m and were located on flat to gently undulating relief. No-tillage systems with crop rotation for over 20 years using soybean and maize during the summer, and wheat and black oats in the winter, were present in the sampled areas.

Three disturbed and undisturbed soil samples were collected at five points in each plot from three layers (0.0 - 0.10, 0.10 - 0.25, 0.25 - 0.40 m). In Ponta Grossa, soil sampling was performed in three years: 2007, 2015 and 2017. In the other sites, the samples were obtained in 2015 and 2017. The disturbed samples were collected with a barrel auger, and the undisturbed samples were collected following the methodology described in Methods of Soil Analysis Manual (Embrapa, 2011) by using stainless steel rings of 59 cm^3 (5 cm diameter and 3 cm height). Samples were wrapped up and stored to preserve natural moisture until analyses.

The granulometry and soil particle density analyses were performed with disturbed samples (**Figure 2**). Clay, silt and sand contents (%) were performed with the pipette method, which is based on the settling velocities of soil particles (Embrapa, 2011). The soil particle density

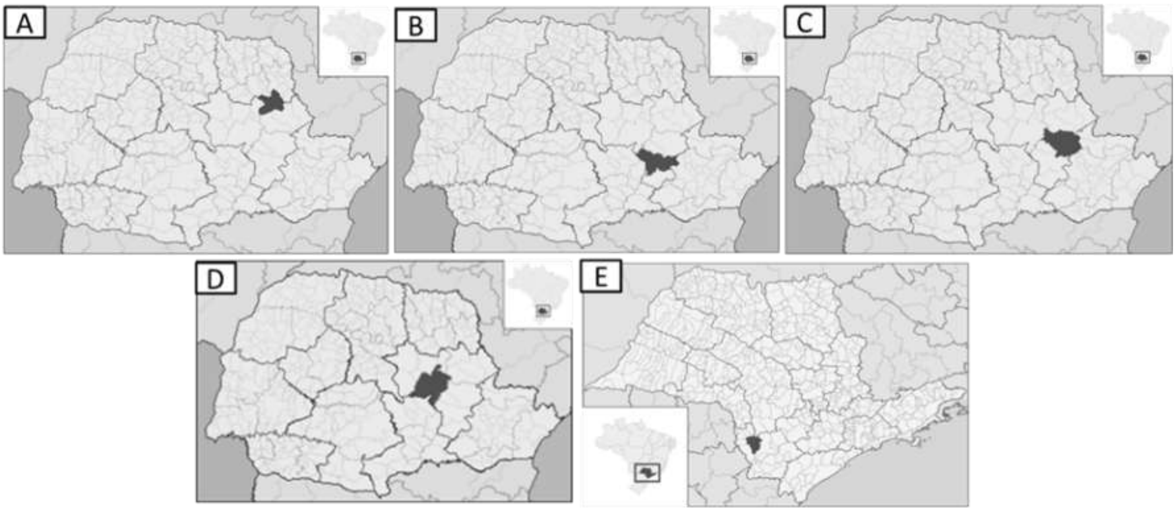

Figure 1. Samples sites located in: (A) Arapoti-PR (Cfa/Cfb climate transition); (B) Ponta Grossa-PR (Cfb climate); (C) Castro-PR and Socavão district (Cfb climate); (D) Tibagi-PR (Cfb climate); and, (E) Itaberá-SP (Cfa climate).
Figura 1. Sitios de muestreo ubicados en: (A) Arapoti-PR (transición climática Cfa/Cfb); (B) Ponta Grossa-PR (clima Cfb); (C) Castro-PR y distrito de Socavão (clima Cfb); (D) Tibagi-PR (clima Cfb); y, (E) Itaberá-SP (clima Cfa).

(kg m^{-3}) was determined using the volumetric flask method, by adding ethanol (92 ° GL) and stirring the sample until the air was expelled from soil pores (Gubiani *et al.*, 2006). The following analysis were performed with the undisturbed samples: soil bulk density (kg m^{-3}) by the ratio of soil dry mass and the ring volume; volumetric moisture at field capacity (θ_{FC}; m^3 m^{-3}); total, macro and microporosity (m^3 m^{-3}), being macropores with diameter larger than 0.05 mm and micropores between 0.05 and 0.0002 mm (Klein & Libardi, 2002); and saturated hydraulic conductivity (mm $hour^{-1}$) (Embrapa, 2011). The total porosity was considered equal to the volumetric soil moisture at saturation (θ_{SAT}). The moisture at field capacity (θ_{FC}) was determined with volumetric rings arranged in the tension table at 0.01 MPa. Soil microporosity was considered equal to θ_{FC} value. The macroporosity was obtained by the difference between θ_{SAT} and θ_{FC} (Fabian & Ottoni Filho, 2000).

The parameters θ_r, a, m and n of the Van Genuchten (1980) equation were estimated with the SPLINTEX pedotransfer program, version 1.0 (Prevedello, 1999). For each soil layer of the studied sites, the following input data were required for the SPLINTEX program: clay (%), silt (%), fine sand (%) and coarse sand (%), soil particle density (kg m^{-3}), soil bulk density (kg m^{-3}), volumetric soil moisture at saturation (θ_S; %). With the parameterized Van Genuchten (1980) equation, the soil water retention curve (*SWRC*) was generated using the statistical *software R* (R Core Team, 2014),

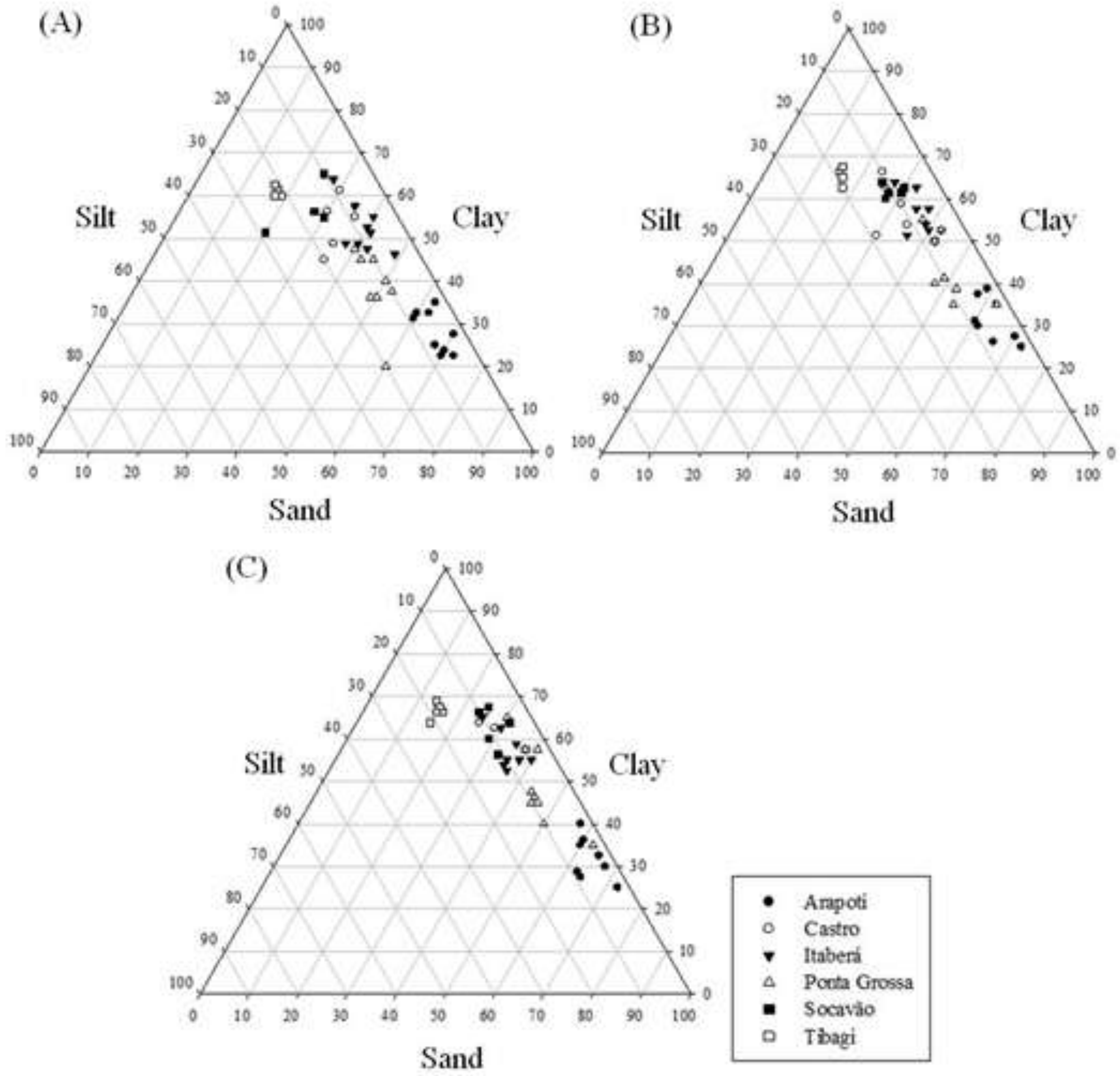

Figure 2. Granulometric distribution of the soil samples collected in the layers: (A) 0.0 - 0.10 m; (B) 0.10 - 0.25 m; and, (C) 0.25 - 0.40 m, from no-tillage systems in the localities of Arapoti, Castro, Ponta Grossa, Socavão and Tibagi - Paraná, and Itaberá - São Paulo, Subtropical region of Brazil.
Figura 2. Distribución granulométrica de las muestras de suelo recolectadas en las capas: (A) 0.0 - 0.10 m; (B) 0.10 - 0.25 m; y, (C) 0.25 - 0.40 m, de sistemas de siembra directa sobre rastrojo en las localidades de Arapoti, Castro, Ponta Grossa, Socavão y Tibagi - Paraná e Itaberá - São Paulo, región Subtropical de Brasil.

for the 0.0 - 0.10 m, 0.10 - 0.25 m and 0.25 - 0.40 m soil layers. It was considered as permanent wilting point (θ_{PMP}) the volumetric moisture obtained at 1.5 MPa pressure, estimated with the Van Genuchten (1980) equation.

The soil available water capacity (*AWC*) was determined with the expression:

$$AWC = \sum_{i=1}^{n} (\theta_{FCi} - \theta_{PWPi}) \cdot z_i$$

Where: *AWC* – soil available water capacity (mm); θ_{FCi} – volumetric soil moisture at field capacity in the *i*-th layer ($m^3\ m^{-3}$); θ_{PMPi} – volumetric soil moisture at the permanent wilting point in the *i*-th layer ($m^3\ m^{-3}$); z_i – *i*-th rooted soil layer depth (mm); *n* – number of layers considered.

Statistical analyses consisted in the determination of trend and data dispersion of the physical and hydraulic soil properties and graph comparisons. The correlation coefficient was also calculated between the absolute values of physical and hydraulic soil properties of the no-tillage systems using the statistical *software R* (R Core Team, 2014).

RESULTS AND DISCUSSION

The soil bulk density (ρ_S) ranged between 1400 kg m^{-3} (Arapoti) to less than 1000 kg m^{-3} (Tibagi) (**Figure 3**). According to Reichardt & Timm (2012), clay soils generally present lower ρ_S than sandy soils, a fact observed in the present study. Arapoti and Ponta Grossa presented higher ρ_S than other localities with higher clay content, like Socavão and Tibagi (**Figure 2**). Overall, the ρ_S tended to be higher in the uppermost layers (0.0 - 0.25 m). Vizioli *et al.* (2021) studying the effects of long-term tillage systems (since 1989) on soil physical quality and crop yield in an Oxisol, located in Ponta Grossa, Parana State, Southern Brazil, observed higher ρ_S values in the layer up to 0.15 m for the conventional and no-tillage systems, and lower values for the strategic tillage (no-tillage with periodical soil chiseling to reduce soil compaction) system. The threshold value separating the high and low ρ_S is 1240 kg m^{-3} for clay soils and about 1650 kg m^{-3} for sandy soils (Pachepsky & Park, 2015). Although high ρ_S values in the soil can be related to compaction, the ρ_S values verified in Arapoti (**Figure 3**) were due to the higher sand content (**Figure 2**), but being below the limit of 1650 kg m^{-3} for sandy soils, suggested by Pachepsky & Park (2015). This indicates that ρ_S data in our study are within a range that does not compromise the soil physical quality.

The soil particle density (ρ_P) is an attribute that does not depend on the management but on the constitution of the parental material. Overall, ρ_P is little variable between soil types and can be between 2300 kg m^{-3} and 2900 kg m^{-3}. The ρ_P values observed in the studied soils (**Figure 3**) were similar to those indicated in the literature for different soil types (Libardi, 2005). The values ranged between 2330 kg m^{-3} (Socavão) to 2721 kg m^{-3} (Itaberá). The lowest ρ_P values were observed in the Histosol sampled in Socavão (2215 kg m^{-3}). The organic matter was not measured, however, Histosols are described as predominantly organic soils (Soil Survey Staff, 2014), with low ρ_P values. In soils presenting significant quartz content in its composition, ρ_P approaches to 2650 kg m^{-3}, similar to the particle density of pure quartz (Reichardt & Timm, 2012).

The average total porosity (α) observed in the studied soils ranged between 0.47 m^3

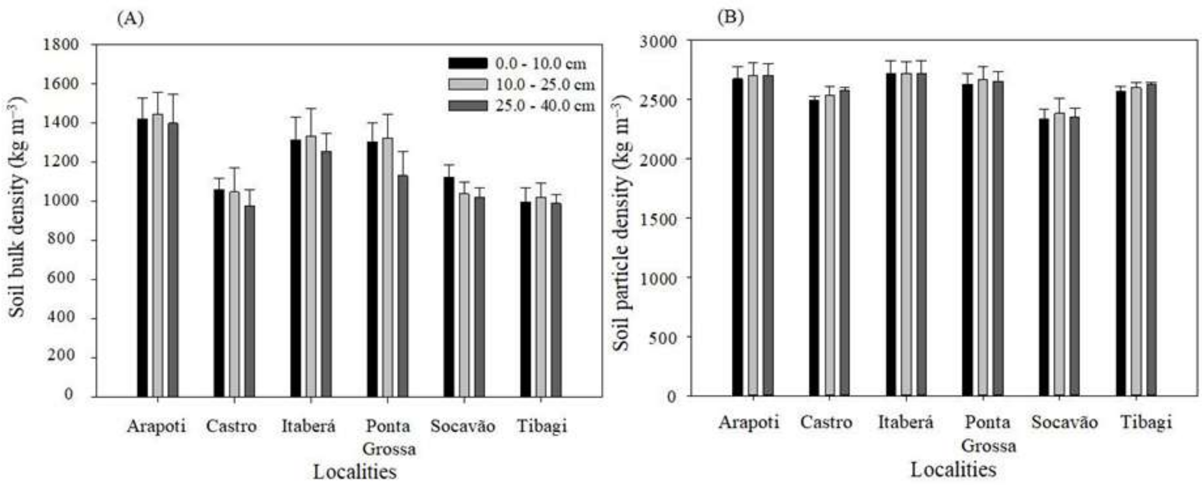

Figure 3. Soil bulk density (A) and soil particles density (B) of samples collected in no-tillage systems in the localities of Arapoti, Castro, Ponta Grossa, Socavão and Tibagi - Paraná State, and Itaberá - São Paulo State, Subtropical region of Brazil.
Figura 3. Densidad aparente del suelo (A) y densidad de partículas del suelo (B) de las muestras recolectadas en sistemas de siembra directa sobre rastrojo en las localidades de Arapoti, Castro, Ponta Grossa, Socavão y Tibagi - Estado de Paraná e Itaberá - Estado de São Paulo, región Subtropical de Brasil.

m^{-3} (Arapoti) and 0.63 m^3 m^{-3} (Castro), in agreement with sandy to clayey soils, respectively (**Figure 4**). Clayey soils usually have *a* between 0.52 m^3 m^{-3} and 0.61 m^3 m^{-3} (Libardi, 2005). The soils in Arapoti presented average values lower than 0.52 m^3 m^{-3}, probably because this was the soil with the highest sand content among those in this study. Loamy soils usually present *a* ranging between 0.47 m^3 m^{-3} and 0.51 m^3 m^{-3} (Reichardt & Timm, 2012).

Ideally, the macropores should occupy one-third of the total soil porosity, while the other two thirds should represent micropores (Hillel, 1970; Reichardt & Timm, 2012). Nevertheless, it also depends on the soil type (Freire, 2006). Therefore, the average values found in the studied soils indicate adequate conditions for agricultural cultivation (**Figure 4**). In most cases, the proportion of macropores and micropores were different than 1/3 and 2/3, respectively, for the studied soils, which may be associated with two factors acting together: *i*) High clay content in the soils, exception made to the samples in Arapoti; and, *ii*) The compaction that may occur in the upper layers of no-tilled soils (Scanlon *et al.*, 2008), in addition to other factors such as disaggregation of the soil structure and a decline in organic matter (Bot & Benites, 2005). High clay contents cause the formation of large volumes of micropores, decreasing the proportion of macropores (Hillel, 1970). Compaction, in its turn, can lead to a decrease in the macropore volume, which could explain the very attenuated macropore/micropore proportions in the uppermost soil layers (except in the samples in Tibagi). However,

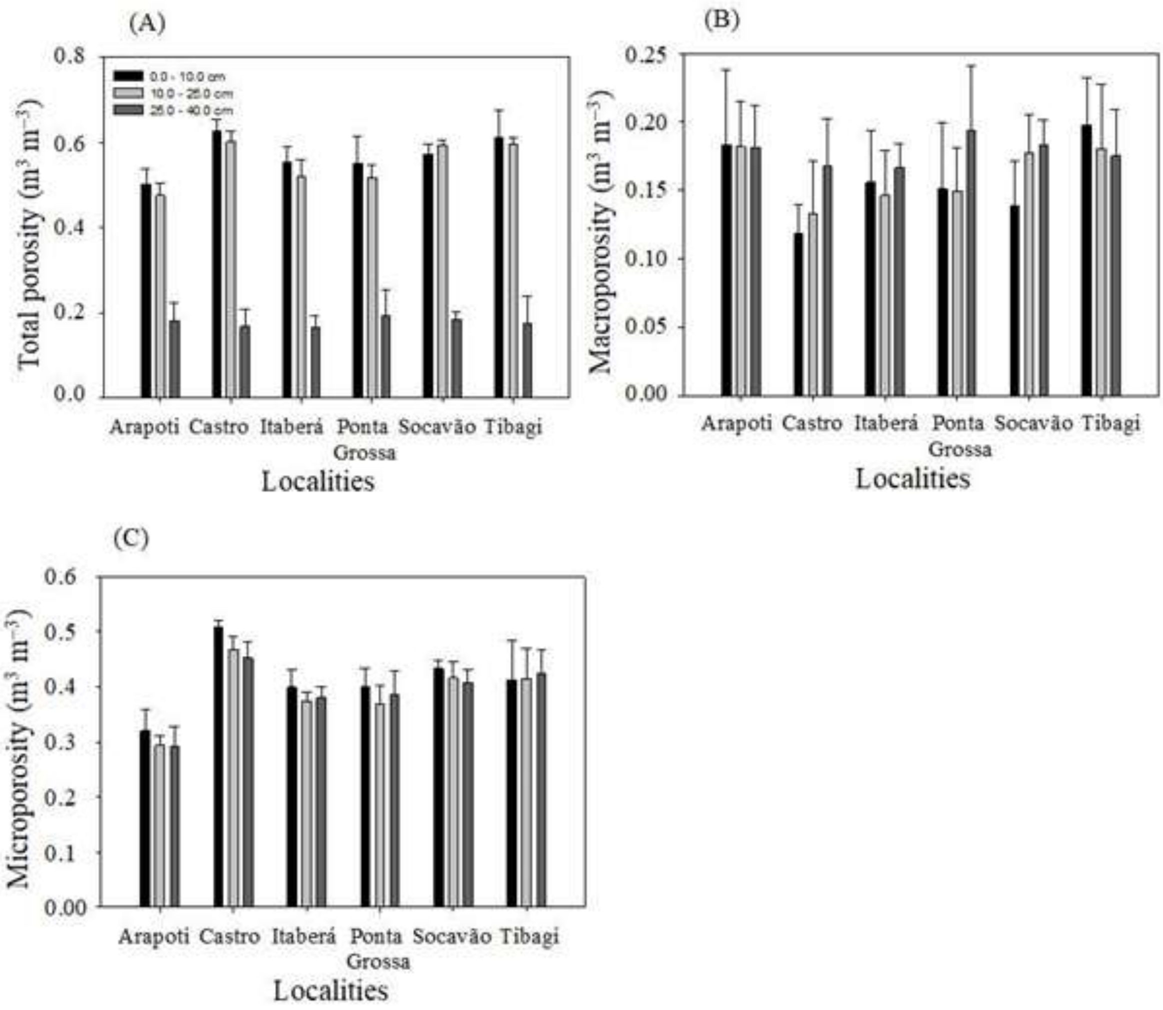

Figure 4. Total (A), macro (B) and microporosity (C) of samples collected in no-tillage systems in the localities of Arapoti, Castro, Ponta Grossa, Socavão and Tibagi - Paraná State, and Itaberá - São Paulo State, Subtropical region of Brazil.
Figura 4. Porosidad total (A), macroporosidad (B) y microporosidad (C) de las muestras recolectadas en sistemas de siembra directa sobre rastrojo en las localidades de Arapoti, Castro, Ponta Grossa, Socavão y Tibagi - Estado de Paraná e Itaberá - Estado de São Paulo, región Subtropical de Brasil.

considering the limits established by Libardi (2005), Freire (2006) and Pachepsky & Park (2015), it can be considered that the sampled soils in this study were not compacted. According to Bognola *et al.* (2010), soils with a higher volume of micropores tend to exhibit more saturated pores, which favor nutrient movement to supply the plant. In absolute values, the average volume of soil macropores indicated a higher aeration potential than the ideal: 0.1 - 0.16 m^3 m^{-3} (Baver *et al.*, 1972; Kiehl 1979; Unger *et al.*, 1982; Reichardt & Timm, 2012).

The average values of volumetric moisture at field capacity (θ_{FC}) ranged between 0.29 m^3 m^{-3} (Arapoti) to 0.50 m^3 m^{-3} (Castro) (**Figure 5B**), while the values of volumetric moisture at permanent wilting point (θ_{PWP}) were 0.15 m^3 m^{-3} (Arapoti) -

0.36 m^3 m^{-3} (Castro) following the same trend observed for θ_{FC} (**Figure 5C**).

The lowest mean *AWC* values (48.5 mm) were observed in soil samples from Tibagi (**Figure 6A**) due to the high volumetric moisture values at the permanent wilting point (**Figure 5**), which is related to a high volume of micropores of small diameter, between 0.05 and 0.0002 mm (Gubiani *et al.,* 2006; Klein & Libardi, 2002; Libardi, 2005). The amplitude between volumetric moisture at field capacity and permanent wilting point, as well as the high values of soil bulk density favored the occurrence of high *AWC* values in the studied soils (**Figure 5A**). The *AWC* values in Ponta Grossa were higher than 60 mm. A similar value was reported by Araujo *et al.* (2009), who estimated an AWC of 68.3 mm for soybean under no-tillage, at the III and IV growth stages.

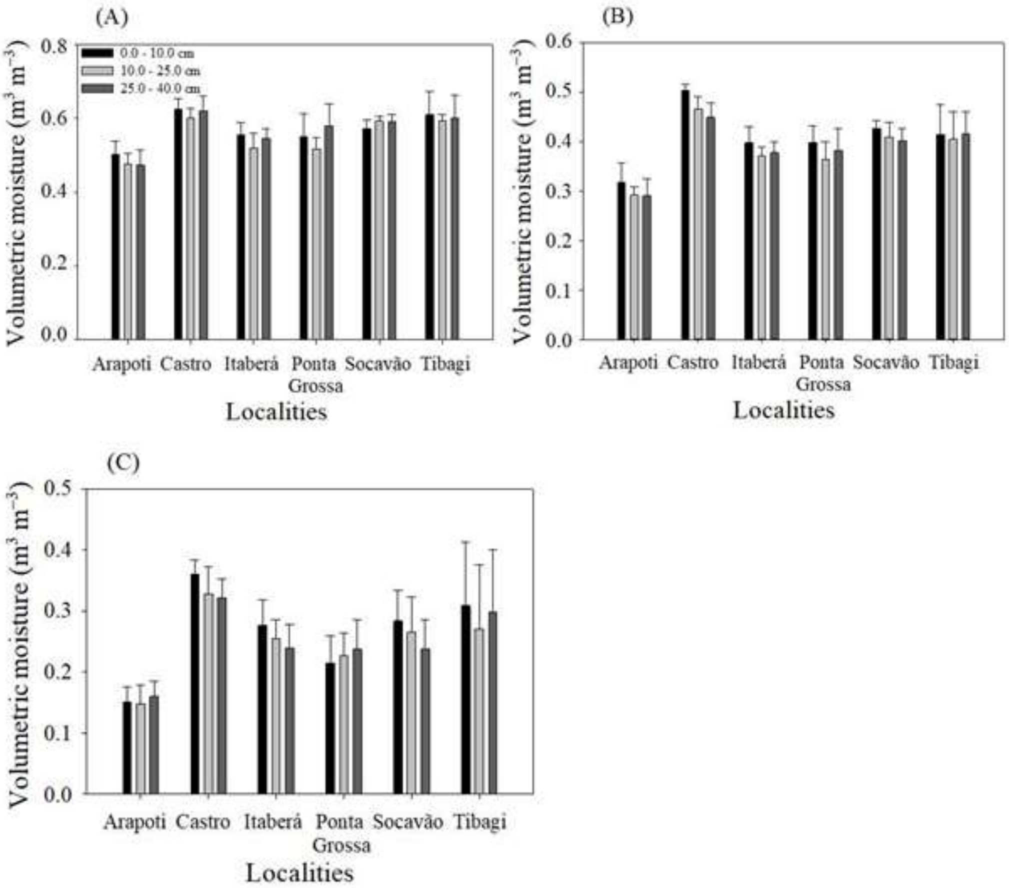

Figure 5. Soil volumetric moisture at saturation (*θsat*; A), field capacity (θ_{FC}; B) and permanent wilting points (θ_{PWP}; C) of samples collected in no-tillage systems in the localities of Arapoti, Castro, Ponta Grossa, Socavão, and Tibagi - Paraná State, and Itaberá - São Paulo State, Subtropical region of Brazil.
Figura 5. Humedad volumétrica del suelo en saturación (*θsat*; A), capacidad de campo (θ_{FC}; B) y puntos de marchitez permanente (θ_{PWP}; C) de las muestras recolectadas en sistemas de siembra directa sobre rastrojo en las localidades de Arapoti, Castro, Ponta Grossa, Socavão y Tibagi - Estado de Paraná, e Itaberá - Estado de São Paulo, región Subtropical de Brasil.

Under no-tillage, the uppermost layer is typically compacted, which has become a recurrent problem (Nawaz *et al.,* 2016; Lima *et al.,* 2018). On the other hand, studies have reported that intensive traffic and soil preparation can cause physical degradation of the soil, influencing its structure and negatively affecting the soil physical indicators (Castioni *et al.*, 2018).

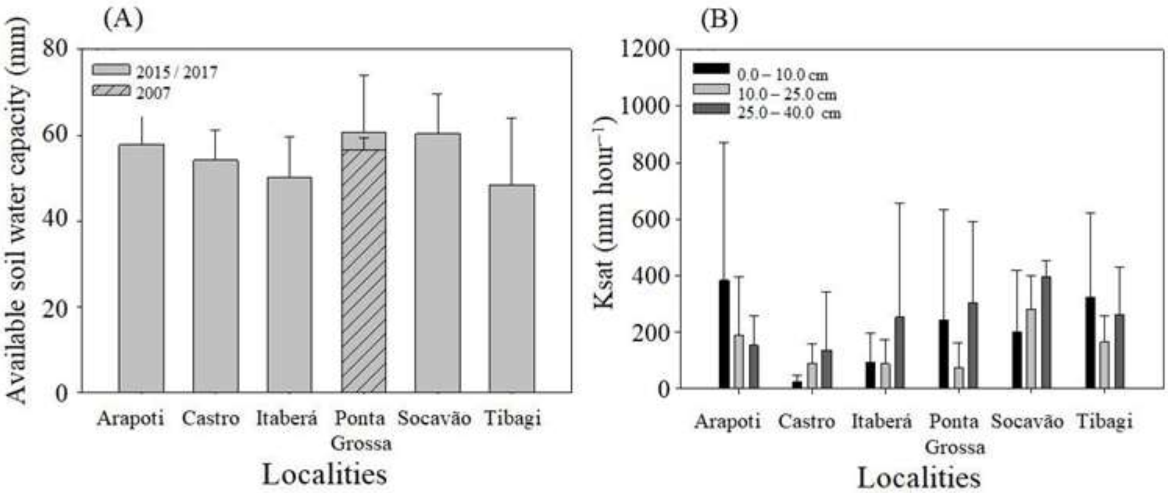

Figure 6. Soil available water capacity (*AWC*; A) and Saturated Hydraulic Conductivity (K_{SAT}; B) of samples collected in no-tillage systems in the localities of Arapoti, Castro, Ponta Grossa, Socavão and Tibagi - Paraná State, and Itaberá - São Paulo State, Subtropical region of Brazil.
Figura 6. Capacidad de agua disponible del suelo (*AWC*; A) y conductividad hidráulica saturada (K_{SAT}; B) de muestras recolectadas en sistemas de siembra directa sobre rastrojo en las localidades de Arapoti, Castro, Ponta Grossa, Socavão y Tibagi - Estado de Paraná e Itaberá - Estado de São Paulo, región Subtropical de Brasil.

The *AWC* of the system in Ponta Grossa estimated in 2007 (Araujo *et al.*, 2009) and about 10 years later revealed a slight increase in the capacity of the soil to store water (**Figure 6A**). However, this effect was not detected after a four-year study by Jabro *et al.* (2016) in a sandy soil submitted to zero tillage. The soil from Ponta Grossa is more clayey, a factor that favors the occurrence of significant changes associated to management (Barbosa *et al.*, 2018). Moreover, we are considering a longer period, when compared to the study of Jabro *et al.* (2016), which reinforces the importance of long term soil monitoring (Cavalcanti *et al.*, 2019).

Soil saturated hydraulic conductivity (K_{SAT}) is known to be scale-dependent (Pachepsky & Park, 2015), which can explain the high variability observed among the samples (**Figure 6B**). The highest average values of K_{SAT} observed in the studied soils were close to 400 mm hour^{-1} in Arapoti and Socavão, while the lowest K_{SAT} values were observed in Castro (23.7 mm hour^{-1}). Castro also presented the lowest standard deviation among the samples. In a soil section, larger pores may not contribute to water infiltration when they are discontinuous and, therefore, macroporosity may often not correlate with water infiltration rate (Bouma, 1982). In Lepsch *et al.* (2015) classification, when considering the degree of permeability, all K_{SAT} values found in the studied soils belongs to the “moderate” group. The absence of values considered extremely high or low indicated that the adopted management of the studied soils was not negatively affecting soil quality.

With data of granulometric fraction (% of sand, silt and clay) and soil bulk density (ρ_S) and particle density as input (ρ_P), the *SPLINTEX* pedotransfer program estimates the parameters of the Van Genuchten equation (**Figure 7**). With the parameters, it was possible to estimate the soil water retention curve (**Figure 8**) for the studied soils, which is fundamental for understanding the impact of management on plant available water in the subtropical region we studied and also for future studies (Koekkoek and Booltink, 1999).

The soil water retention curve (*SWRC*) describes the association between

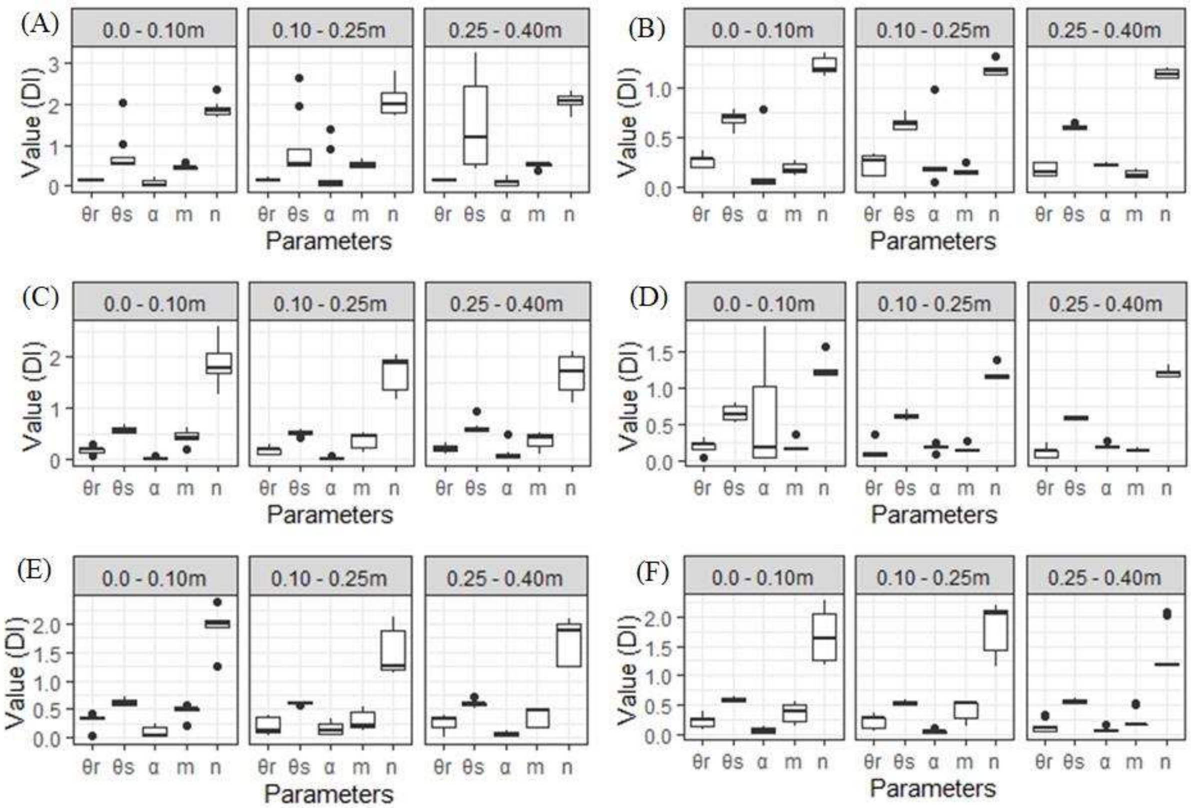

Figure 7. Parameters of the Van Genuchten equation obtained with the SPLINTEX pedotransfer program in the localities of Subtropical region of Brazil: (A) Arapoti; (B) Castro; (C) Ponta Grossa; (D) Socavão; (E) Tibagi; and, (F) Itaberá.
Figura 7. Parámetros de la ecuación de Van Genuchten obtenidos con el programa de pedotransferencia *SPLINTEX* en las localidades de la región Subtropical de Brasil: (A) Arapoti; (B) Castro; (C) Ponta Grossa; (D) Socavão; (E) Tibagi; e (F) Itaberá.

volumetric content and the energy with which water is retained in soil particles. The *SWRC* trend reflected the porosity classes of the evaluated soils. The results showed that as the highest is the amount of micropores, the highest is the tension required to cause water loss from a soil volume, as observed in Castro (**Figures 4C** and **8B**). For soils with a predominance of macropores, such as Arapoti (**Figure 4B**), water loss occurred in smaller potentials and the asymptote was more evident (**Figure 8A**).

The highest correlation observed in the present study occurred between the θ_{FC} and the volume of soil micropores (**Table 1**), which was naturally expected, since the microporosity values were considered the same as the θ_{FC} values, in agreement with results obtained by Andrade & Stone (2011). The authors also found a high correlation between these two attributes in their study with more than two thousand soil samples. Fabian & Ottoni Filho (2000), using the same relationship, validated an equation to estimate the θ_{FC} from micropores volume of an Ultisol.

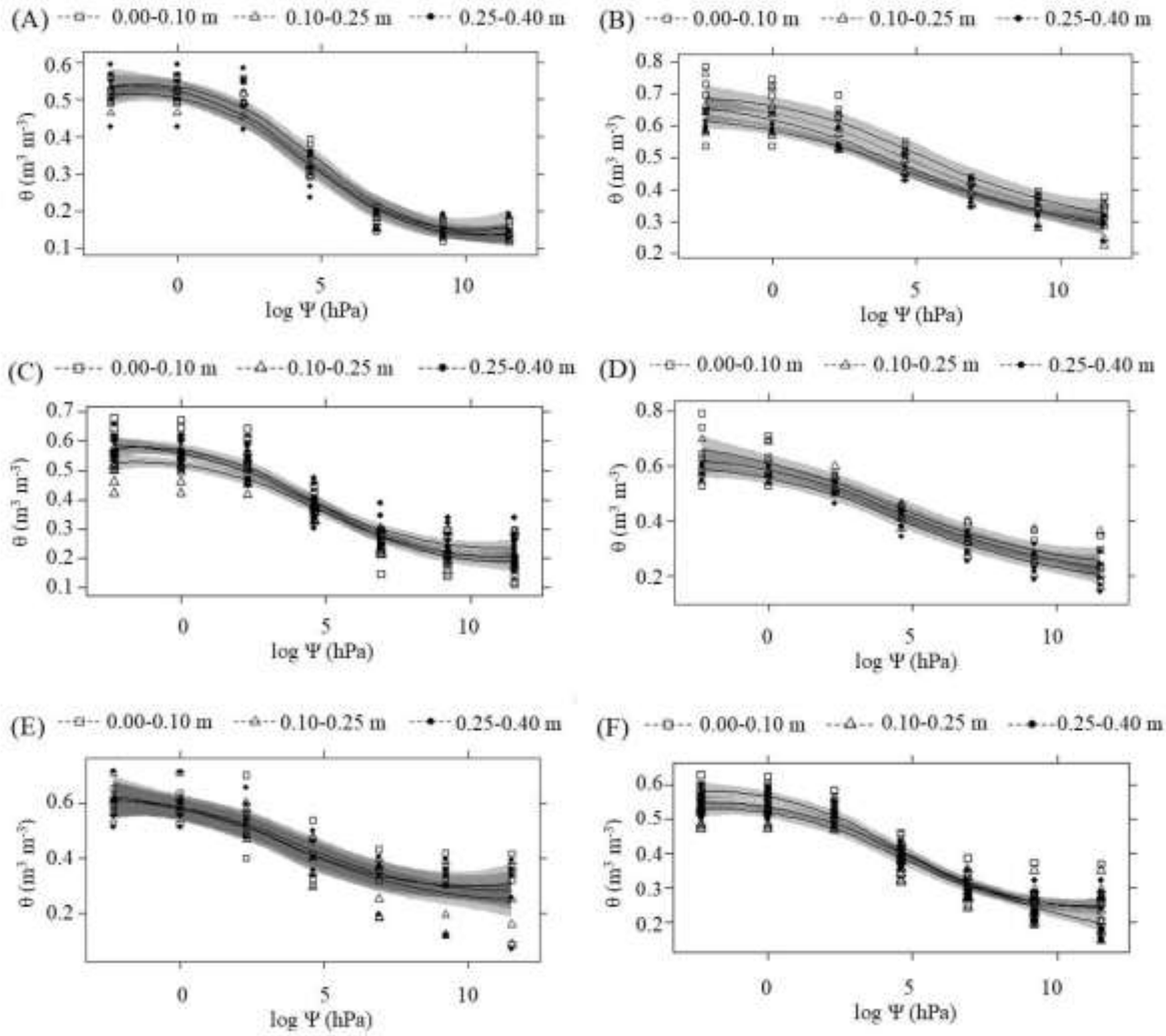

Figure 8. Soil water retention curve (*SWRC*) obtained with the Van Genuchten equation and parameters estimated with the SPLINTEX pedotransfer program in localities of Subtropical region of Brazil: (A) Arapoti; (B) Castro; (C) Ponta Grossa; (D) Socavão; (E) Tibagi; and, (F) Itaberá.
Figura 8. Curva de retención de agua del suelo (*SWRC*) obtenida con la ecuación de Van Genuchten y parámetros estimados con el programa de pedotransferencia *SPLINTEX* en localidades de la región Subtropical de Brasil: (A) Arapoti; (B) Castro; (C) Ponta Grossa; (D) Socavão; (E) Tibagi; y, (F) Itaberá.

Table 1. Correlation coefficient between the absolute values of soil physical and hydraulic properties of samples collected from no-tillage systems in the localities of Arapoti, Castro, Ponta Grossa, Socavão and Tibagi - Paraná State, and Itaberá - São Paulo State, Subtropical region of Brazil.
Tabla 1. Coeficiente de correlación entre los valores absolutos de las propiedades física e hidráulicas del suelo de muestras recolectadas en sistemas de siembra directa sobre rastrojo en las localidades de Arapoti, Castro, Ponta Grossa, Socavão y Tibagi - Estado de Paraná, e Itaberá - Estado de São Paulo, región Subtropical de Brasil.

Attribute	ρ_s (1)	ρ_{ps} (2)	α (3)	Porosity		θ_{SAT} (4)	θ_{PWP} (5)	θ_{FC} (6)	K_{sat} (7)	Clay	Silt	Sand
				micro	macro							
ρ_s	1.00	0.56*	-0.70*	-0.57*	-0.16	-0.70*	-0.46*	-0.55*	-0.12	-0.68*	-0.44*	0.70*
ρ_{ps}		1.00	-0.25*	-0.35*	0.16	-0.25*	-0.20*	-0.33*	0.07	-0.32*	-0.23*	0.34*
α			1.00	0.78*	0.30*	1.00*	0.54*	0.77*	0.27*	0.56*	0.48*	-0.62*
Porosity micro				1.00	-0.37*	0.78*	0.76*	1.00*	-0.15	0.61*	0.50*	-0.66*
Porosity macro					1.00	0.30*	-0.36*	-0.37*	0.63*	-0.09	-0.04	0.09
θ_{SAT}						1.00	0.54*	0.77*	0.27*	0.56*	0.48*	-0.62*
θ_{PWP}							1.00	0.77*	-0.11	0.61*	0.40*	-0.63*
θ_{FC}								1.00	-0.14	0.59*	0.50*	-0.65*
K_{sat}									1.00	-0.05	0.06	0.02
Clay										1.00	0.40*	-0.95*
Silt											1.00	-0.66*
Sand												1.00

A narrow correlation was also found between θ_{PWP} and microporosity. The result indicates that most of the total porosity of the studied soils consisted of micropores, being directly related to soil water retention (Reichardt & Timm, 2012). Carter (1988) found that, under low pressure, the macropore water moves faster and under the high stresses the macropores become full of air while the water in the micropores is still trapped. Therefore, under high pressure, soil water retention is controlled by its micropore volume.

The micropores act directly on soil water retention. As the proportion of soil micropores is higher, more difficult is the water movement. For this reason, the tension required for the water movement in this soil condition is higher. Therefore, soils with a predominance of micropores, when subjected to less water stress for plants, present little water movement and the value of θ_{FC} and θ_{PWP} tend to be high. Thus, these attributes tend to have a close positive correlation (Cavenage *et al.*, 1999; Hillel 1970).

The K_{SAT} of the studied soils were closely correlated with macropores. Generally, K_{SAT} correlates well with soil macropore volume, as it is the medium where water moves most easily along the profile (Mesquita & Moraes, 2004). However, as the studied soils showed a reduced relative volume of macropores,

K_{SAT} was positively correlated with the sand content and negative with the clay content.

The θ_{FC} and θ_{PWP} showed a close positive correlation, which is naturally expected since they are attributes that depend on the same sources of variation (Libardi, 2005). The clay, silt and sand contents also showed a significant ($p < 0.05$) correlation. The negative correlation observed for sand was expected, since it is a fraction of the total soil texture, i.e., when the value of one increases the other tend to decrease.

The availability of data related to the soil physical and hydraulic properties is important for researchers and technicians. Reliable data on physical and hydraulic soil properties are fundamental to guide and assist numerous investigations, as well as contributing to decision-making on the best agricultural practices to be carried out to maintain or improve the soil quality and crop production.

CONCLUSIONS

The crop management under no-tillage for more than 20 years in the subtropical region of Brazil did not result in deterioration of soil physical quality, considering the eleven physical and hydraulic soil properties (granulometric distribution; soil bulk density; soil particle density; total, macro and microporosity; volumetric moisture at field capacity, permanent wilting point and saturation; available water capacity; and saturated hydraulic conductivity) and their acceptable limits established in the literature. Even considering a set of contrasting soil types, the average soil bulk density and soil porosity fall within typical limits that do not restrict the development of annual crops. The proportion between micro and macropores does not differentiate much from the 2:1, considered ideal for good soil aeration and water storage. A variable requiring attention is the saturated hydraulic conductivity, whose figures indicated it is at “moderate” levels.

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