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Physical quality of sandy soils under orange orchards in Southern Brazil

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ABSTRACT: Sandy soils are characterized by low organic matter content and soil water retention and availability. Conventional tillage has been used for the implementation of orange orchards, but it exposes the soil to erosion and promotes accelerated oxidation of organic matter with negative impacts on the soil's physical quality. The objective of this study was to evaluate the soil physical quality of sandy soils influenced by two soil tillage practices for planting the orange trees in areas after long-time under pastures. Soil sampling was carried out in three experimental areas (one under Lixisol and two under Ferralsol) where the planting of orange trees had been carried out using two tillage practices: (i) conventional tillage in total area; and (ii) localized conventional tillage in a strip corresponding to the orange tree planting lines. A complete randomized design was used with two treatments (total or strip tillage) and four replications. Disturbed and undisturbed soil samples were taken in 2011 (8 to 18 years after the establishment of the treatments) from the 0.00-0.10 and 0.10-0.20 m layers in transects crossing: (i) under canopy projection below orange trees; (ii) under machine wheel tracks in the interrow of the orange trees; and (iii) under grass groundcover between the wheel tracks in the interrow of the orange trees. The following determinations were made for these samples: texture analysis, total organic carbon, soil bulk density, reference bulk density obtained with saturated soil subjected to a 200 kPa, soil resistance to penetration, soil water content, and water retention curves and the least limiting water range. The results suggest that total tillage for the implantation of orange orchards is unnecessary; however, after a long time of establishing orange orchards occurs soil physical quality discontinuity under wheel tracks compared to the other sampling positions. A positive correlation between organic carbon and soil physical quality was identified under the canopy of trees and grass groundcover in the interrow of the orange trees. For similar sand content, the higher soil organic carbon in the Ferralsol provided better physical quality than in Lixisol.

Keywords: organic carbon, citrus, LLWR, minimum tillage, soil compaction.

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INTRODUCTION

Approximately 8 % of Brazilian land area is characterized as sandy soil, corresponding to the sand, loamy-sand or sandy-loam textural classes up to a depth of 0.75 m or more, belonging to the *Neossolos Quartzarênicos* (Arenosols), *Latossolos* (Ferralsols) and *Argissolos* (Lixisols), according to the Brazilian System of Soil Classification (Donagemma et al., 2016). In the Northwest region of the state of Paraná, Southern, there are approximately 30,000 km² of sandy soils, corresponding to 16 % of the State's area (Fidalski and Helbel Junior, 2020). These soils are formed by rocks belonging to the Caiuá Group, which is formed by the Paraná River, Goioerê and Santo Anastácio geological formations (Etchebehere et al., 2007), and referred to locally as the Arenito Caiuá. The classes of soils representative of Caiuá group are the Ferralsols, Lixisols and Arenosols which are in catenas located between the water divisions up to the drainage networks and are characterized, in the same sequence, by an increase in sand content in the superficial layer (Thomaz and Fidalski, 2020). These soils are predominantly fine sands, providing weak aggregation and low water retention capacity (Fidalski and Helbel Junior, 2020). Under agricultural use, there is an even greater reduction in organic matter levels and the physical quality of these soils due to soil compaction (Fidalski et al., 2010).

The predominant use of these sandy soils in the Northwest of Paraná, Southern Brazil, is in line with their agricultural suitability for beef cattle pasture, despite the low cattle stock (Arantes et al., 2018). However, agricultural use has been intensified by cultivating soybean, sugar cane, cassava (Volsi et al., 2020) and orange (Costa et al., 2020). Orange orchards established on pastures using conventional tillage in the orange tree planting lines, i.e., soil tillage in strip 2 m in width, promoted a reduction in soil disturbance of up to 70 % in the tilled area, constituting a soil conservation practice that provides soil and water conservation as well as adequate crop productivity (Mo et al., 2019; Cerdà et al., 2021). Furthermore, these authors found that the maintenance of grassy vegetation in the interrow of the orange trees reduced erosion, and Fidalski et al. (2010) verified the mitigation of the effects of soil compaction by the traffic of machines used in the management of orchards.

In sandy soils, industry representatives have observed that to produce a ton of concentrated orange juice, a greater amount of orange fruit is required when the orchards are planted in soils with higher coarse sand contents (anonymous). Bruand et al. (2005) argue that, in tropical sandy soils, small changes in the texture composition can lead to significant differences in the physical properties of the soils. However, Hondebrink et al. (2017) demonstrated that, in sandy soils, these effects are associated with the magnitude of variability of the soil composition. The results of the physical evaluations of soils under orange orchards cultivated in Lixisol in Southern Brazil (Fidalski et al., 2010) corroborate these findings since the maintenance of cover plants in the interrow of citrus orchards contributes to the improvement of the soil physical quality. Cover crops are management strategies widely practiced in the interrow of orange orchards (Crézé and Horwath, 2021).

Conservation management systems for improving the physical quality of soil under citrus orchards recommend maintaining the interrow vegetation cover, especially with grasses (Hondebrink et al., 2017). The production of biomass and the architecture of the root system of grasses maintain or increase the level of organic carbon, and, therefore, higher water content and lower soil resistance to penetration for the roots of the rootstocks used in citriculture (Homma et al., 2012; Novara et al., 2019).

In the intensively mechanized Brazilian orchards, machine traffic has an impact on the quality physical of soils, as many machines pass per year for orchard management operations (Lima et al., 2004; Fidalski et al., 2010), resulting in up to 45 interrow passes in the first three years of orange tree cultivation. These last authors found that in the first three years after the orange trees were planted, there was the random of machine

traffic because there was more space between the lines of orange trees. From the fourth year, after the formation of the orchards, the traffic of machines occurs in permanent tracks to the projections of the canopy of the orange trees, which is identified in the field by the deformation of the soil surface with the formation of two grooves characteristic of the tire wheels of tractors and sprayers.

Studies carried out in orange orchards on Ferralsol and Lixisol sandy soils have found that soil resistance to penetration (PR) was the physical property that most often reduces the least limiting water range (LLWR), mainly in pastures areas (Flávio Neto et al., 2015; Benevenuto et al., 2020). In this context, these Ferralsols and Lixisols are differentiated by the presence of Bw and Bt horizons, in which different proportions of sand contents in the surface layer were verified (Fidalski and Helbel Junior, 2020; Thomaz and Fidalski, 2020). The reference bulk density has been frequently used to evaluate the degree of compaction (D_c) under different soils and management systems (Etana et al., 1999; Reichert et al., 2009).

The objective of this study was to evaluate the soil physical quality of sandy soils influenced by two soil tillage practices for planting the orange trees in areas after a long-time under pastures.

MATERIALS AND METHODS

The soil samples were obtained from experiments dedicated to the study of tillage practices for the establishment of the orange trees in Alto Paraná (23° 5' S; 52° 26' W), Paranavaí (23° 6'; 52° 25' W) and Nova Esperança (23° 6' S; 52° 25' W), in the Northwest region of the State of Paraná, Southern Brazil, in soils with sandy texture at 0.20 m depth, which were classified as *Argissolo Vermelho distrófico* (Lixisol; loamy-sand), *Latossolo Vermelho distrófico* (Ferralsol; loamy-sand) and *Latossolo Vermelho distrófico* (Ferralsol; sandy-loam) according to Santos et al. (2013) and IUSS Working Group WRB (2006), respectively. The soils are derived from weathered residues of the Alogrupo Rio Paraná from Arenito Caiuá, of the São Bento series, from the Cretaceous period. The three soils showed a predominance for the fine sand fraction and low organic carbon levels in the 0.00-0.20 m layer (Table 1). The climate in the region is classified as Cfa, with an average

Table 1. Texture characterization for three soils irrespective of two tillage practices, layers, and transect sampling positions (n = 108 samples)

Descriptive statistics	Fine sand ⁽¹⁾	Coarse sand ⁽²⁾	Total sand	Silt	Clay
	g kg ⁻¹				
Lixisol loamy-sand					
Minimum	640	80	840	10	70
Mean	747	132	879	17	104
Maximum	830	220	910	30	150
Ferralsol loamy-sand					
Minimum	720	50	850	10	70
Mean	785	102	887	13	101
Maximum	860	190	920	20	140
Ferralsol sandy-loam					
Minimum	630	50	750	10	140
Mean	705	99	804	12	183
Maximum	790	180	850	20	230

⁽¹⁾ 0.02-0.2 mm. ⁽²⁾ 0.2-2 mm (Santos et al., 2005).

annual precipitation of 1300-1600 mm and temperature of 20-22 °C, and is characterized by droughts, with rain concentrated in the spring and summer (Alvares et al., 2013).

Before the implantation of the treatments, the experimental areas were cultivated with the pastures formed by forages such as Koroniviagrass [*Brachiaria humidicola* (Syn. *Urochloa humidicola*)], Bahiagrass (*Paspalum notatum*) and Palisadegrass [*Urochloa brizantha* (Syn. *Brachiaria brizantha*)], planting in 1993, 1994 and 2003, respectively, on Lixisol, Ferralsol loamy-sand and Ferralsol sandy-loam. The field experiments were established in a complete randomized design. The experimental plots consisted of three rows of five orange trees, respectively, about 7 × 4 m. The soil tillage treatments were preceded by surface liming with dolomitic limestone distributed over the total area in doses that increased the base saturation to 70 %. The treatments consisted of two tillage practices: (i) conventional tillage in total area – total tillage; and (ii) conventional tillage in the orange tree planting lines in strip 2 m wide – strip tillage. The soil tillage consisted of plowing with a disc plow at a depth of 0.20 m, followed by leveling with harrows. After establishing the orchards, the management of weeds in the interrow of the orchards was carried out by mechanized mowing without disrupting the soil throughout the experimental period. Planting orange trees, disease and pest control, mowing, liming, fertilizing, and harvesting were carried out using a tractor, making the furrow with a mass of 3,500 kg.

To determine the D_c , disturbed and undisturbed soil samples were collected from the 0.00-0.10 m and 0.10-0.20 m layers from three positions of transects and triplicates by the experimental plot: (i) under canopy projection in lines of orange trees – canopy projection position; (ii) under machine wheel tracks in the interrow of the orange trees – wheel tracks position; and (iii) under grass groundcover between the wheel tracks in the interrow of the orange trees – grass groundcover position, respectively, 1.5, 2.5 and 3.5 m away from the trunk of the orange trees. The soil samples were collected in the experimental plots from three blocks, providing 36 soil samples in each of the experiments, totaling 108 soil samples in the three experiments. Undisturbed samples were collected using steel cylinders 5 cm in height and diameter. Disturbed soil samples were also collected using a Dutch auger, then sieved in a 2 mm diameter sieve and used to determine the texture measurements using the pipette method (sand, silt and clay) and the organic carbon using the Walkley-Black method. Sand content was divided into two fractions: fine sand (0.02-0.2 mm) and coarse sand (0.2-2 mm). In the laboratory, part of these samples was used to determine the reference bulk density, which consisted of placing soil in steel cylinders (2.5 cm high × 7.2 cm in diameter), followed by their saturation for 24 h. Subsequently, the samples were submitted to compression in an automated consolidometer, according to Silva et al. (2007). Soil samples were maintained under a pressure of 200 kPa for 45 min to obtain soil deformation (Håkansson, 1990). Then, the samples were dried in an oven at 105 °C for 48 h to obtain the dry soil mass which was used to compute the soil bulk density (B_d), taken here as the maximum soil bulk density or the reference bulk density (D_r). The D_c was calculated from the values of B_d and D_r : [$D_c = (B_d / D_r) \times 100$ (%)].

During the first half of 2011, thereabout 8, 17 and 18 years after the establishment of the orange orchards, respectively, in Lixisol, Ferralsol loamy-sand and Ferralsol sandy - loam (Table 1), two samplings of undisturbed soil samples were taken simultaneously from the three experiments: one to determine the LLWR and the other for the D_c . To determine the LLWR, 108 undisturbed soil samples were collected from the three experiments using stainless steel cylinders (5 cm in height and diameter). The samples were taken from the 0.00-0.10 and 0.10-0.20 m layers of the canopy projection, the wheel tracks and grass groundcover sampling positions. These samples were used to determine the water content (θ), D_c and penetration resistance (PR). The samples were saturated and allowed to dry naturally in the laboratory at 25 °C. During drying, for the different θ of the soil samples, individual PR measurements were taken with a bench penetrometer

(0.04 m diameter cone, 60° angle and 0.05 m high rod) similar to that described by Tormena et al. (1999). Then, to determine the matric potentials (h), a mini-tensiometer with a porous capsule 0.05 m in diameter was introduced into the holes formed by the penetrometer penetration of the rod. For the soil samples that exceeded the reading capacity of the tensiometer, a Dewpoint Potential Meter, model WP4-T (Decagon Devices, Inc., 2007), was used for h measurements, according to Ojeda et al. (2013). Then, soil samples were placed in an oven at 105 °C for 48 h, followed by the determination of water and soil masses to allow the calculation of Bd and θ .

The results of the determinations made on the undisturbed samples were used to adjust the water retention and soil resistance to penetration curves, which were used to estimate the LLWR. The set of 108 Bd (Mg m^{-3}) observations, with respective θ ($\text{m}^3 \text{m}^{-3}$) at different h (hPa) and PR (MPa), independent of tillage treatment, layer, sampling position and soil type was used to obtain curves for water retention and soil resistance to penetration using models described by Silva et al. (1994). The soil water retention curves were determined by equation 1.

$$\theta = a|h|^b \quad \text{Eq. 1}$$

It was fitted with the model parameters (a and b) and the Bd was integrated into the model using the parameter a ($a_0 Bd^{a_1}$), with a_0 and a_1 being the coefficients. The soil resistance to penetration curve was fitted using the equation 2.

$$\text{PR} = c\theta^d Bd^e \quad \text{Eq. 2}$$

After applying a logarithmic transformation at equation 2, we obtained equation 3.

$$\ln \text{PR} = \ln c + d \ln \theta + e \ln Bd \quad \text{Eq. 3}$$

in which c , d and e are the fitted parameters (t-test; $p < 0.05$). The fitting of these curves and the LLWR values was performed using the R soil physics package, according to Lima et al. (2020).

The limits of the physical properties used to estimate the LLWR were: air-filled porosity ($\theta_{\text{AFP}} = 0.10 \text{ m}^3 \text{ m}^{-3}$), permanent wilting point ($\theta_{\text{PWP}} = -15000$ hPa) and θ_{PR} (2 MPa), according to Silva et al. (1994). The θ equivalent to field capacity (θ_{FC}) was estimated at soil h of -30 hPa, as suggested for Brazilian soils by Turek et al. (2020).

The data of Bd , Dc , LLWR and organic carbon were submitted to analysis of variance by the mathematical model of complete randomized blocks, and the mean values of these variables were compared between two tillage practices and three positions of transects by the Tukey's test ($p < 0.05$) and; Pearson's correlation coefficient (r) was performed for each of the soils between the organic carbon with Bd , Dc and LLWR ($n = 36$) by t-test ($p < 0.05$), according to Banzatto and Kronka (2006).

RESULTS

Maximum soil density or reference soil bulk density at 200 kPa did not differ significantly, except Lixisols loamy-sand, which presented lower reference soil density than the Ferralsol sandy-loam at 0.10-0.20 m layer (Table 2). There was greater reference soil density in the wheel tracks position than in the canopy projection position for Ferralsol loamy-sand.

Soil bulk density (Bd) significantly influenced the water retention and penetration resistance curves (Table 3). With the increase in Bd between 1.24-1.82 Mg m^{-3} , there was a reduction in LLWR associated with a reduction in θ_{AFP} and θ_{FC} and an increase in θ_{PWP} and θ_{PR} (Figure 1). The Bd amplitudes were smaller for Ferralsol loamy-sand,

followed by Lixisols loamy-sand than Ferralsol sandy-loam (Tables 4, 5 and 6). However, in the LLWR calculation, it was possible to verify common Bd values between 1.57 and 1.80 $Mg\ dm^{-3}$ for the three sandy soils studied. The average Bd values were not influenced by tillage strategies (total and strip tillages) in Lixisol loamy-sand and Ferralsol loamy-sand (Tables 4 and 5), except in Ferralsol sandy-loam in the sampling position relative to wheel tracks and in the 0.00-0.10 m depth layer (Table 6). In this soil, it was found that total tillage increased Bd compared to strip tillage, respectively,

Table 2. Mean values for maximum soil bulk density or the reference bulk density at 200 kPa in three sampling positions and two depth layers of three soils

Soil	Mg m ⁻³		
	Canopy projection	Wheel tracks	Grass groundcover
0.00-0.10 m layer			
Lixisols loamy-sand	1.64 a	1.59 a	1.58 a
Ferralsol loamy-sand	1.76 a	1.77 a	1.78 a
Ferralsol sandy-loam	1.85 a	1.88 a	1.84 a
0.10-0.20 m layer			
Lixisols loamy-sand	1.65 a	1.64 a	1.63 a
Ferralsol loamy-sand	1.79 b	1.87 a	1.84 ab
Ferralsol sandy-loam	1.88 a	1.88 a	1.89 a

Means followed by the same letters in the lines do not differ by the Tukey test ($p < 0.05$).

Table 3. Soil water retention and soil resistance to penetration curves adjusted to three soils at the depth of 0.20 m (Equations 1 and 2)

Equations
Soil water retention curve: $h = e^{0.34-0.56*Bb} \theta^{-0.25**}$
Soil resistance to penetration curve: $PR = 0.0127 h^{-1.26**} Bd^{5.03*}$

(* $p < 0.05$) and (** $p < 0.01$) significant by t-test.

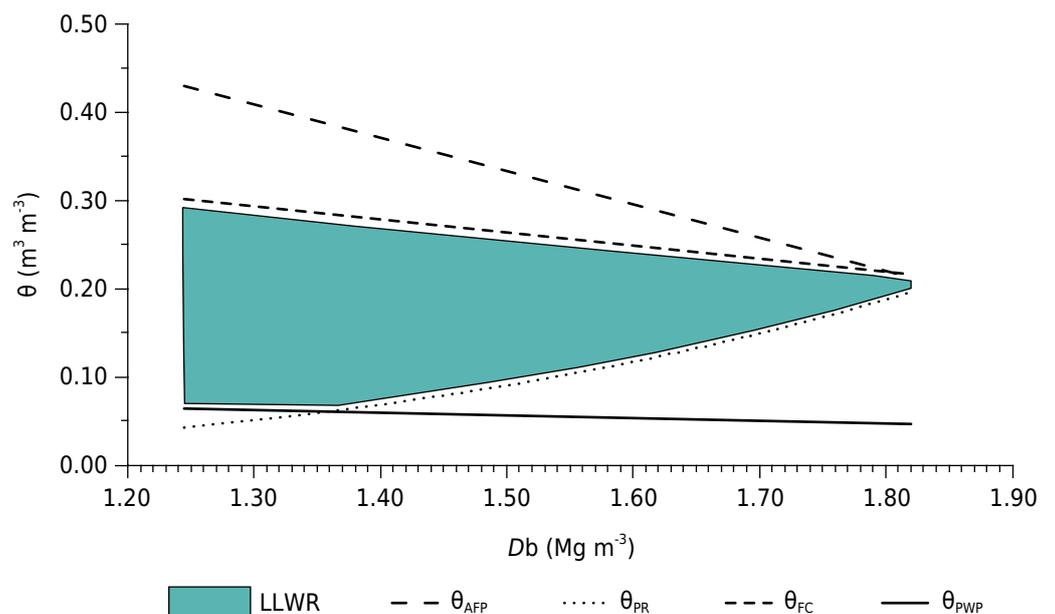


Figure 1. Values of water content (θ) as a function of soil bulk density (Bd) to the three soils at 0.20 m layer depth irrespective tillage practices and sampling positions at field capacity ($\theta_{FC} = 30$ hPa), wilting point ($\theta_{PWP} = 15000$ hPa), airfilled porosity ($\theta_{AFP} = 0.10\ m^3\ m^{-3}$) and soil resistance to penetration ($\theta_{PR} = 2$ MPa). The LLWR corresponds to the least limiting water range.

Table 4. Mean values for soil bulk density (*Bd*), degree of compaction (*Dc*), least limiting water range (LLWR) and organic carbon for total tillage and strip tillage in three sampling positions and two depth layers of Lixisol loamy-sand

<i>Bd</i>		<i>Dc</i>		LLWR		Carbon	
Total	Strip	Total	Strip	Total	Strip	Total	Strip
Mg m ⁻³		%		m ³ m ⁻³		g kg ⁻¹	
Canopy projection position (0.00-0.10 m layer)							
1.48 a	1.50 a	92 a	90 a	0.12 a	0.11 a	5.2 a	5.2 a
Canopy projection position (0.10-0.20 m layer)							
1.56 a	1.54 a	93 a	95 a	0.12 a	0.10 a	3.7 a	3.7 a
Wheel tracks position (0.00-0.10 m layer)							
1.62 a	1.63 a	102 a	103 a	0.11 a	0.11 a	5.0 a	5.6 a
Wheel tracks position (0.10-0.20 m layer)							
1.74 a	1.76 a	107 a	107 a	0.06 a	0.05 a	3.4 a	3.5 a
Grass groundcover position (0.00-0.10 m layer)							
1.56 a	1.56 a	97 a	100 a	0.08 a	0.10 a	4.3 a	5.5 a
Grass groundcover position (0.10-0.20 m layer)							
1.66 a	1.66 a	102 a	101 a	0.05 a	0.06 a	3.1 a	3.3 a

Means followed by the same letters in the lines for tillage practices do not differ by the Tukey test ($p < 0.05$).

Table 5. Mean values for soil bulk density (*Bd*), degree of compaction (*Dc*), least limiting water range (LLWR) and organic carbon for total tillage and strip tillage in three sampling positions and two depth layers of Ferralsol loamy-sand

<i>Bd</i>		<i>Dc</i>		LLWR		Carbon	
Total	Strip	Total	Strip	Total	Strip	Total	Strip
Mg m ⁻³		%		m ³ m ⁻³		g kg ⁻¹	
Canopy projection position (0.00-0.10 m layer)							
1.52 a	1.52 a	88 a	85 a	0.16 a	0.16 a	8.3 a	9.1 a
Canopy projection position (0.10-0.20 m layer)							
1.63 a	1.60 a	90 a	90 a	0.12 a	0.13 a	6.2 a	6.5 a
Wheel tracks position (0.00-0.10 m layer))							
1.71 a	1.73 a	100 a	95 a	0.08 a	0.07 a	8.9 a	9.1 a
Wheel tracks position (0.10-0.20 m layer)							
1.77 a	1.76 a	93 a	96 a	0.04 a	0.06 a	5.9 a	6.5 a
Grass groundcover position (0.00-0.10 m layer)							
1.51 a	1.57 a	84 a	88 a	0.12 a	0.15 a	8.9 a	8.9 a
Grass groundcover position (0.10-0.20 m layer)							
1.65 a	1.64 a	91 a	88 a	0.12 a	0.11 a	5.9 a	6.5 a

Means followed by the same letters in the lines for tillage practices do not differ by the Tukey test ($p < 0.05$).

from 1.77 to 1.83 Mg dm⁻³. However, this increase in *Bd* did not influence the LLWR after 18 years of establishing the orange orchard. The effect of total tillage on soil compaction was not confirmed by the *Dc* and soil organic carbon (Tables 4, 5 and 6).

Regardless of the tillage practice, there was wide variability in soil physical quality indicators *Bd*, *Dc* and LLWR obtained in the transects, with the exception of the LLWR in the 0.00-0.10 m layer in the Lixisol loamy-sand and organic carbon for the three soils in the 0.00-0.10 and 0.10-0.20 m layers (Figure 2). In the sampling position relative to the wheel tracks position, there was an increase in *Bd* and *Dc* and a reduction in LLWR compared to the sampling position relative to the canopy projection position in

Table 6. Mean values for soil bulk density (*Bd*), degree of compaction (*Dc*), least limiting water range (LLWR) and organic carbon for total tillage and strip tillage in three sampling positions and two depth layers of Ferralsol sandy-loam

<i>Bd</i>		<i>Dc</i>		LLWR		Carbon	
Total	Strip	Total	Strip	Total	Strip	Total	Strip
Mg m ⁻³		%		m ³ m ⁻³		g kg ⁻¹	
Canopy projection position (0.00-0.10 m layer)							
1.38 a	1.38 a	75 a	74 a	0.18 a	0.20 a	9.3 a	9.3 a
Canopy projection position (0.10-0.20 m layer)							
1.58 a	1.56 a	83 a	84 a	0.17 a	0.14 a	7.2 a	6.9 a
Wheel tracks position (0.00-0.10 m layer)							
1.83 a	1.77 a	95 a	96 a	0.05 a	0.03 a	8.5 a	8.8 a
Wheel tracks position (0.10-0.20 m layer)							
1.77 b	1.80 a	93 a	96 a	0.07 a	0.04 a	6.4 a	6.4 a
Grass groundcover position (0.00-0.10 m layer)							
1.64 a	1.66 a	90 a	90 a	0.11 a	0.12 a	8.3 a	9.1 a
Grass groundcover position (0.10-0.20 m layer)							
1.68 a	1.70 a	88 a	91 a	0.10 a	0.09 a	6.7 a	6.1 a

Means followed by the same letters in the lines for tillage practices do not differ by the Tukey test ($p < 0.05$).

Ferralsol loamy-sand and Ferralsol sandy-loam (Figure 2). The indicators *Bd*, *Dc* and LLWR of the position grass groundcover position showed greater variability compared to the other sampling positions (Figure 2). Regardless of the sampled layer, in the sampling positions relative to the canopy projection and the wheel tracks sampling positions, these physical soil quality indicators are equal to or lower than those under the grass groundcover position.

For both soils, the *Dc* ranged from 75 to 107 %, reaching values higher than 100 % in the Lixisol loamy-sand under the wheel tracks sampling position at 0.00-0.10 m and 0.10-0.20 m and grass groundcover sampling position at 0.10-0.20 m (Figure 2), because of lower maximum soil density or reference soil density in Lixisol than in Ferrasols (Table 2). The *Dc* under wheel tracks were significantly higher than under canopy projection position. Higher *Dc* was found at 0.00-0.10 and 0.10-0.20 m layer of the Lixisol loamy-sand and at the 0.00-0.10 m layer of the Ferralsol loamy-sand under the wheel tracks and grass groundcover sampling positions compared to the sampling position corresponding to the canopy projection position.

Soil organic carbon contents of the 0.00-0.20 m depth layer of the three soils were negatively correlated ($r > 0.50$) with *Dc* and positively with LLWR under the canopy projection and grass groundcover sampling positions (Figure 3).

DISCUSSION

Soil organic carbon and moisture (Table 1) are within the variability of soils in the Northwest region of the state of Paraná, Southern Brazil (Fidalski and Helbel Junior, 2020). The organic carbon content remained statistically equal between the three sampling positions for the three soils after 8-18 years after the establishment of the orange orchards, in line with Conant et al. (2017).

The effect of tillage practices on *Bd* in Ferralsol sandy-loam (Table 6) agrees with the results described by Neves et al. (2010) in similar soil in the same region as this study. The presence of forages in the interrow provided advantages found in conservation systems developed for citrus based on maintaining interrow vegetation cover by

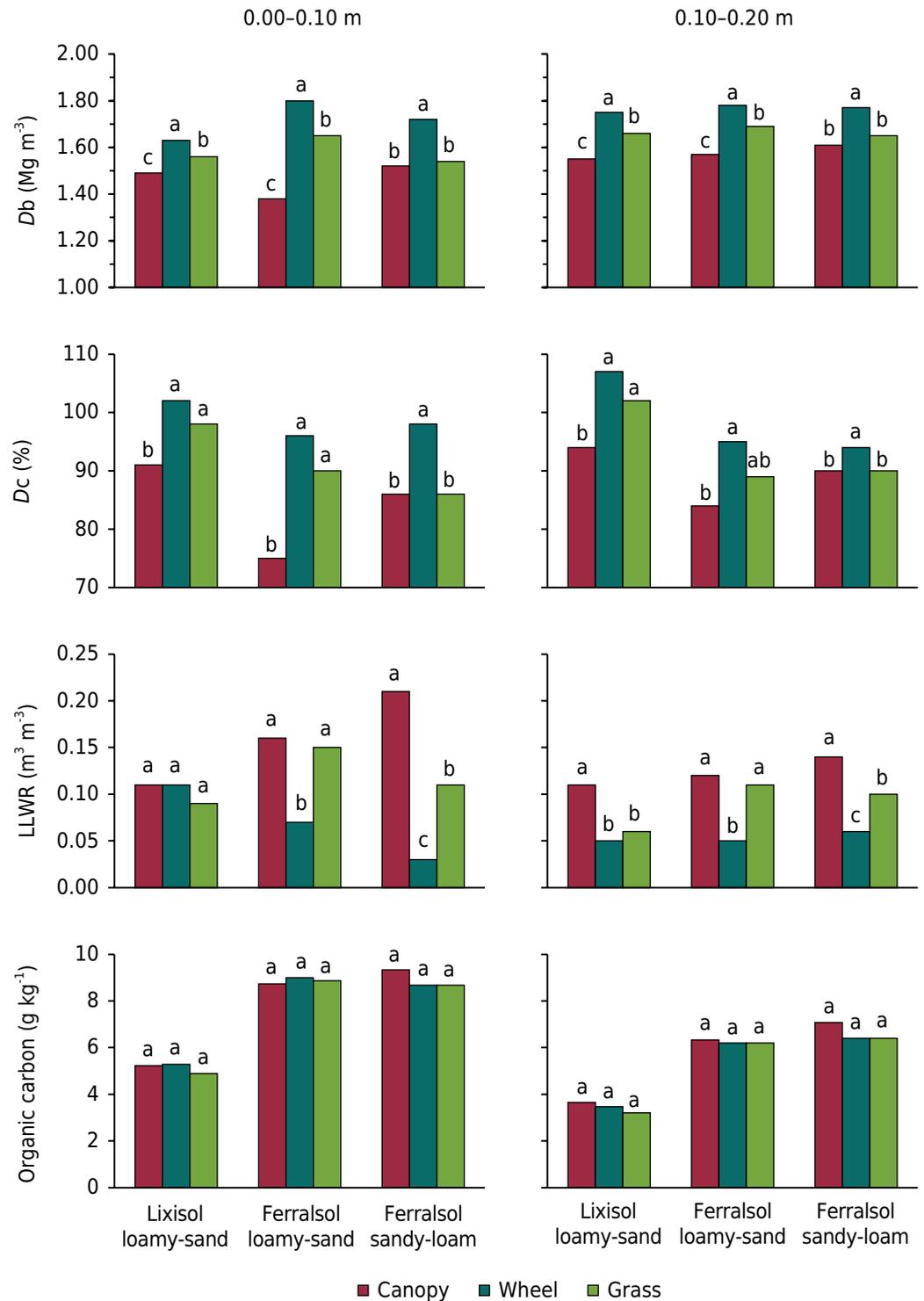


Figure 2. Mean values for soil bulk density - *Bd*, degree of compaction - *Dc*, least limiting water range - *LLWR* and organic carbon at 0.00-0.10 and 0.10-0.20 m depth layer of Lixisol loamy-sand, Ferralsol loamy-sand and Ferralsol sandy-loam, in three sampling position of transects: canopy projection, wheel tracks and grass groundcover, independently of the two tillage practices. Means followed by equal letters in the columns for soil, do not differ by the Tukey test ($p < 0.05$).

grasses (Fidalski et al., 2010; Homma et al., 2012; Hondebrink et al., 2017). In line with Mo et al. (2019), the risk of erosion during the implantation phase of the orange groves would decrease in these sandy soils due to the maintenance of pasture grasses between the orange orchards' interrow.

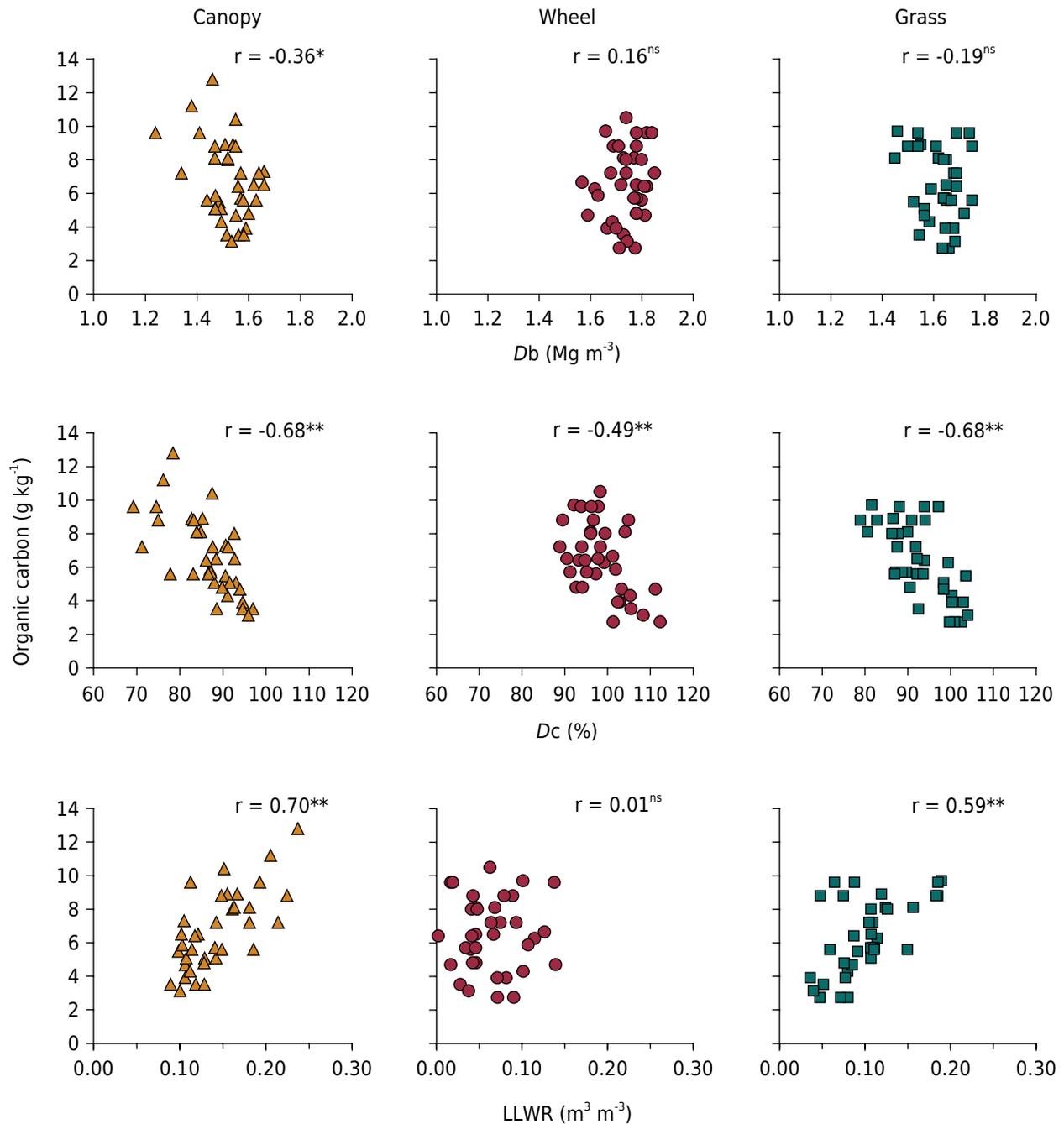


Figure 3. Soil bulk density - *Bd*, degree of compaction - *Dc* and least limiting water range - *LLWR* correlated with the organic carbon by sampling position in each of the three soils, respectively, in three sampling positions: canopy projection, wheel tracks and grass groundcover. Pearson's correlation coefficient (*r*): (***p*<0.01), (**p*<0.05) and (^{ns}: non-significant) by *t*-test.

The results of this study show that tillage conventional should be avoided throughout the area to establish orange orchards under pastures (Neves et al., 2010), considering the results of soil physical quality and the indifference in orange yield in these three experiments established without or with soil tillage in the inter-rows of orange orchards in pastures from Caiuá Sandstone (Auler and Fidalski, 2013).

These results made it possible to characterize a greater horizontal and vertical variability of *Bd* with the reduction of the sand content of the Lixisol loamy-sand and Ferralsol loamy-sand in relation to the Ferralsol sandy-loam (Figure 2; Tables 1 and 4). An increase in *Bd* due to machinery traffic in the interrow of orange orchards in Ferralsol sandy-loam (Fidalski et al., 2007) and Lixisol loamy-sand has been reported by Fidalski et al. (2010).

A higher D_c was found under the wheel tracks than in the canopy projection position to three soils, and D_c reached values above 100 % in the Lixisol loamy-sand under wheel tracks position at 0.00-0.10 and 0.10-0.20 m at grass groundcover sampling position (Figure 2), which are associated with lower organic carbon and higher sand contents in Ferralsol sandy-loam (Tables 1, 4, 5 and 6). The reduction in the D_c with an increase in organic matter and clay content agrees with the results of Marcolin and Klein (2011). Differences in the D_c between soil classes were also reported by Etana et al. (1999). Reichert et al. (2009) also found a D_c greater than 100 % for tropical soils with clay contents similar to the Lixisol, and Suzuki et al. (2007) in Alfisol sandy due to high levels of soil compaction in this soil. In our study, the Ferralsols presented the lowest D_c at 0.20 m depth in the canopy projection position (75-94 %) than in the wheel tracks position (94-107 %), allowing us to characterize an adequate physical environment under the canopy projection than grass groundcover sampling positions.

These physical quality indicators did not depend on the organic carbon contents ($r < 0.50$) under the wheel track position. These results also suggest that the organic carbon content also promoted a decrease in the D_c and increase in the LLWR under the canopy projection position in the 0.00-0.10 and 0.10-0.20 m layers and grass groundcover position in the 0.10-0.20 m layer (Figures 2 and 4). Thus, the physical degradation of the soil under the wheel tracks position due to the greater intensity of machine traffic in soils with more sand content, expressed by the reduction in LLWR (Table 1; Figures 1, 2 and 3), was confirmed.

The physical quality indicators of the three soils were not limiting for orange yield (Auler and Fidalski, 2013). Furthermore, the organic carbon contents did not differ between the two tillage practices, sampling positions and soil layers. However, the results suggest that the physical quality indicators of these three sandy soils were dependent on soil organic carbon, similar to the observations of Di Prima et al. (2018), who suggested that tillage treatments should be avoided in established orange orchards.

Management practices for these soils should establish a diminished traffic intensity or employ strategies to run the machinery with greater load-bearing capacity, especially on soils consisting of clayey-sand texture. Covering the soil between orange rows with grass species such as Signalgrass and Palisadegrass is another option for mitigating the damage to the soil structure by the machinery traffic as they provide biological soil decompaction and consequently increase the availability of water for orange trees (Flávio Neto et al., 2015). Recently, other authors have confirmed the mitigation of soil compaction through management with grasses {Signalgrass [*Brachiaria decumbens* (Syn. *Urochloa decumbens*)] and Palisadegrass} in Brazilian tropical soils (Oliveira et al., 2016; Silva et al., 2021). Thus, strategies to reduce the intensity of soil tillage during the establishment of orchards, maintenance of living and dead vegetation cover in the interrow and better distribution of machinery traffic in orchard interrows (Neves et al., 2010; Azevedo et al., 2020) contribute to physical and water improvements through conventional tillage only in the orange tree planting lines to establishment of orchards in pastures, because of the effects of grasses in maintaining the physical quality of the soil (Hondebrink et al., 2017).

CONCLUSIONS

Physical quality indicators of the sandy soils suggest that soil tillage for the establishment of orange orchards is unnecessary in areas previously under pastures. After establishing orange groves for a long time, machinery traffic increases the B_d , the D_c and reduces the LLWR, regardless of soil and organic carbon content. There was a positive and significant correlation between organic carbon and soil physical quality under the canopy projection position and grass groundcover sampling positions. For similar sand

contents, the higher organic carbon content in Ferralsol showed less compaction in the orange orchard than Lixisol.

The conventional tillage in total area compromised the physical quality expressed by the *Bd* in the Ferralsol sandy-loam under the wheel tracks position. The variability of the indicators *Bd*, *Dc* and LLWR measured in the transects showed discontinuity in the transects, with better soil physical quality under the canopy projection position compared to the sampling positions relative to the wheel tracks position. Due to the similarities between the sand and organic carbon contents, Ferralsol presented better physical quality than Lixisol.

AUTHOR CONTRIBUTIONS

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