Revista Brasileira de Ciência do Solo
ISSN: 0100-0683
revista@sbcs.org.br
Sociedade Brasileira de Ciência do Solo
Brasil

Bernabé Ferreira, Camila Jorge; Tormena, Cássio Antonio; Henrique Moreira, Wagner; Zotarelli, Lincoln; Betioli Junior, Edner; Anghinoni, Guilherme

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Revista Brasileira de Ciência do Solo, vol. 40, 2016, pp. 1-12
Sociedade Brasileira de Ciência do Solo
Viçosa, Brasil

Revista Brasileira de Ciência do Solo

Division - Soil Use and Management | Commission - Soil and Water Management and Conservation

Sampling Position under No-Tillage System Affects the Results of Soil Physical Properties

Camila Jorge Bernabé Ferreira[(1)*], Cássio Antonio Tormena[(2)], Wagner Henrique Moreira[(1)], Lincoln Zotarelli[(3)], Edner Betioli Junior[(1)] and Guilherme Anghinoni[(1)]

[(1)] Universidade Estadual de Maringá, Departamento de Agronomia, Programa de Pós-Graduação em Agronomia, Maringá, Paraná, Brasil.
[(2)] Universidade Estadual de Maringá, Departamento de Agronomia, Maringá, Paraná, Brasil.
[(3)] University of Florida, Department of Horticulture, Gainesville, Florida, United States.

ABSTRACT: Understanding the spatial behavior of soil physical properties under no-tillage system (NT) is required for the adoption and maintenance of a sustainable soil management system. The aims of this study were to quantify soil bulk density (BD), porosity in the soil macropore domain (PORp) and in the soil matrix domain (PORm), air capacity in the soil matrix (ACm), field capacity (FC), and soil water storage capacity (FC/TP) in the row (R), interrow (IR), and intermediate position between R and IR (designated IP) in the 0.0-0.10 and 0.10-0.20 m soil layers under NT; and to verify if these soil properties have systematic variation in sampling positions related to rows and interrows of corn. Soil sampling was carried out in transect perpendicular to the corn rows in which 40 sampling points were selected at each position (R, IR, IP) and in each soil layer, obtaining undisturbed samples to determine the aforementioned soil physical properties. The influence of sampling position on systematic variation of soil physical properties was evaluated by spectral analysis. In the 0.0-0.1 m layer, tilling the crop rows at the time of planting led to differences in BD, PORp, ACm, FC and FC/TP only in the R position. In the R position, the FC/TP ratio was considered close to ideal (0.66), indicating good water and air availability at this sampling position. The R position also showed BD values lower than the critical bulk density that restricts root growth, suggesting good soil physical conditions for seed germination and plant establishment. Spectral analysis indicated that there was systematic variation in soil physical properties evaluated in the 0.0-0.1 m layer, except for PORm. These results indicated that the soil physical properties evaluated in the 0.0-0.1 m layer were associated with soil position in the rows and interrows of corn. Thus, proper assessment of soil physical properties under NT must take into consideration the sampling positions and previous location of crop rows and interrows.

Keywords: crop row, crop interrow, spectral analysis.

*** Corresponding author:**
E-mail: camilajbferreira@gmail.com

Received: July 9, 2015
Approved: September 21, 2015

How to cite: Ferreira CJB, Tormena CA, Moreira WH, Zotarelli L, Betioli Junior E, Anghinoni G. Sampling Position under No-Tillage System Affects the Results of Soil Physical Properties. Rev Bras Cienc Solo. 2016;v40:e0150189.

INTRODUCTION

No-tillage system (NT) is recognized as an important soil management practice for the sustainability of intensive agricultural production systems. NT is based on the absence of intensive tillage, requiring crop rotation and maintenance of residues from the previous crop on the soil surface (Lal, 2004). As a management system, NT has many benefits compared to systems that use intensive soil tillage, such as higher soil water infiltration and water availability to plants, less soil erosion and nutrient loss, reduced working time of machines and fuel consumption, and reduced pollution of water resources (Lal, 2004; Soane et al., 2012).

For many years, great effort has been made to measure and compare soil physical properties in NT and other tillage systems (Almeida et al., 2008), as well as in different crop rotation strategies (Lanzanova et al., 2007; Silveira et al., 2008). The soil physical quality and functionality of pore space depends on the evolution of the system. Recent studies indicated that soil structure improves with time of NT adoption (Reichert et al., 2016), with higher air permeability, hydraulic conductivity and soil water infiltration in response to continuity of the soil pore system in NT (Lal, 2004; Reichert et al., 2016).

Furrow opening for crop sowing in NT promotes localized soil mobilization in the sowing rows. Mobilization intensity depends on the type of equipment used for seed and fertilizer placement (Silva et al., 2014). The opening of furrows for sowing, especially with the use of a furrow opener (also known as knife or tine), modifies soil physical properties to a depth of 0.10 to 0.12 m, creating an environment with distinct soil physical properties compared to regions farther from the furrows. However, the persistence of these soil physical modifications depends on machinery traffic, natural processes in the soil (such as wetting and drying cycles), and biological activity (Gregory et al., 2007).

During sowing under NT, soil mobilization during the furrow opening process promotes an improvement in soil physical characteristics of the seedbed, which may eliminate the need for future soil mechanical interventions (e.g., plowing) in the area and may maintain crop yield levels over the years (Cardoso et al., 2007). Generally, increase in soil organic matter and development of a continuous and stable soil pore system mitigates the negative impacts of soil compaction under NT systems (Cardoso et al., 2007; Betioli Junior et al., 2012). Studies have shown that sowing rows were characterized by lower soil bulk density (BD) and soil root penetration resistance (Correchel et al., 1999; Betioli Junior et al., 2012) compared to crop interrows.

Most research in NT does not take into consideration the position of soil sampling in regard to soil mobilization in the sowing row, or absence of mobilization in the region of the crop interrow. Generally, studies in NT assume that soil sampling was carried out at the center of the interrow, which may be subject to the effects of crop rows and/or interrows that had occurred in that same sampling position. Some authors reported that, on the soil surface layer, the use of random sampling in NT to quantify BD is not enough to isolate the effects of the crop rows and interrow positions on soil properties (Correchel et al., 1999; Betioli Junior et al., 2012). There are no studies indicating which soil properties are more susceptible to the influence of sampling locations and how these changes in physical properties might affect the physical environment for development of plants in NT. The absence of intensive soil disturbance in NT and the presence of more than 80 % of the crop roots in the 0.00-0.20 m layer (Cardoso et al., 2007) highlights the importance of conducting more detailed soil sampling to better understand the effect of localized soil disturbance in the sowing row on overall soil properties under NT. Thus, it is necessary to assess whether the changes in soil physical properties under NT occur randomly or systematically, and to quantify the changes in soil physical properties as a function of the soil layer and sampling position.

The hypothesis of this study was that soil physical properties related to water retention and aeration exhibit systematic variation related to the sampling positions in the crop rows and interrows in the 0.0-0.1 and 0.1-0.2 m layers. The aims of this study were to: (a) quantify soil bulk density (BD), porosity in the soil macropore domain (PORp) and soil matrix domain (PORm), air capacity in the soil matrix (ACm), field capacity (FC), and soil water storage capacity (FC/TP) in the sampling position in the crop row (R), interrow (IR), and intermediate position between R and IR (IP) in the 0.0-0.10 and 0.10-0.20 m layers; and (b) verify if these soil physical properties have systematic variation according to the sampling positions related to crop rows and interrows of corn.

MATERIAL AND METHODS

Soil sampling was carried out on a commercial grain production farm located in Maringá, state of Paraná, Brazil, at 23° 30′ 29.40″ S latitude and 51° 59′ 48.52″ W longitude, altitude of 454 m asl, and flat relief (average slope of 3 %). The soil was identified as *Latossolo Vermelho Distroférrico* (Santos et al., 2013), a Rhodic Hapludox (Soil Survey Staff, 2014). Granulometric analysis of the 0.0-0.2 m layer indicated 750 g kg^{-1} of clay, 50 g kg^{-1} of silt, and 200 g kg^{-1} sand. The dominant climate type, according to the Köppen classification, is mesothermal humid subtropical. The average annual temperature and rainfall are 22 °C and 1,450 mm, respectively.

A 50 ha field under NT since 1979 was selected for this study. In that period of time, crop rotations involved soybean (*Glycine max* L.), wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), and oats (*Avena sativa* L.). Prior to sampling, the area was cultivated with corn for two consecutive crop seasons (summer and winter). During the first 30 years after conversion to NT, limestone was applied based on soil tests. The limestone was broadcast on the soil surface without any mechanical incorporation. Fertilizers were applied at planting with a fertilizer seeder equipped with front straw cutting discs and shanks with parabolic shape, 20° angle of attack, tip of 20 mm thickness, and penetration depth between 0.10 and 0.12 m. In the sampled area, the traffic of tractors, harvesters, and sprayers occurred randomly.

Soil sampling was carried out in September 2010, after the harvest of the winter crop of corn. The distance between corn rows was 0.90 m. Soil samples were taken in a 72 m transect perpendicular to the corn rows. Forty undisturbed soil cores were taken from each of the three sampling position related to the crop row (R); crop interrow (IR), located at 0.45 m from the R; and an intermediate position (IP), established at 0.23 m from the R (Figure 1).

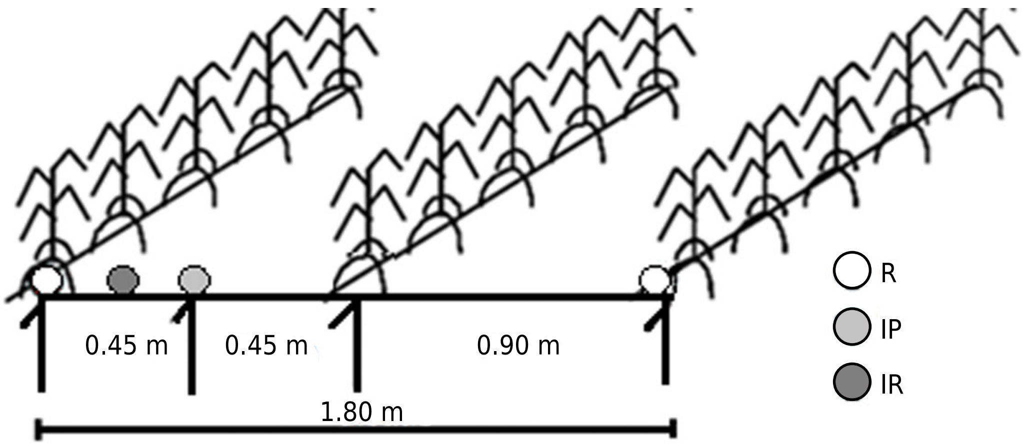

Figure 1. Sampling methodology scheme of undisturbed soil samples along a transect perpendicular to the corn rows in the sampling positions in the row (R), interrow (IR) and intermediate position (IP).

Demarcation of the sampling points was made along transect according to crop row and interrow positions; a crop row was marked as the starting point and used as a basis for collecting the subsequent R, IP, and IR. The distance between two rows sampled was 1.80 m (Figure 1). The undisturbed soil cores were taken with an electro-mechanical automatic sampler (Figueiredo, 2010) to ensure physical and structural integrity of the soil sample. Soil samples were collected with 220 cm^3 metal cylinders. One hundred and twenty samples were collected from the 0.0-0.1 and 0.1-0.2 m layers, for a total of 240 samples. Sample preparation consisted of removing excess soil from the edges of each cylinder. These samples were then saturated for 48 h with gradual elevation of the water level, up to about two-thirds of the sample height.

After saturation, the samples were weighed and subjected to the matric potential of -1, -6, and -10 kPa using a tension table similar to that described by Ball and Hunter (1988). After attaining hydraulic equilibrium at each matric potential, the samples were weighed again. Subsequently, the samples were oven dried at ±105 °C for 24 h to obtain the solid weight and water weight in the soil. The BD was calculated from the ratio between the weight of solids and the sample volume, as described by Grossman and Reinsch (2002).

Total porosity (TP) was calculated as the difference between the saturated soil weight and the dry soil weight divided by the sample volume according to equation 1.

$$TP = (w_{ssat} - w_{ss})/Vt \qquad \text{Eq. 1}$$

where, TP is total porosity (m^3 m^{-3}), w_{ssat} is saturated soil weight (kg kg^{-1}), w_{ss} is dry soil weight (kg kg^{-1}), and Vt is total cylinder volume (m^3 m^{-3}).

Field capacity (FC), or soil water content after hydraulic equilibrium at matric potential of -10 kPa, was determined according to equation 2.

$$FC = (w_{su(-10\ kPa)} - w_{ss})/Vt \qquad \text{Eq. 2}$$

where, FC is field capacity (m^3 m^{-3}), $w_{su(-10\ kPa)}$ is soil weight at matric potential of -10 kPa (kg), w_{ss} is dry soil weight (kg), and Vt is total cylinder volume (m^3).

Soil physical properties were determined as described by Reynolds et al. (2002) as follows: a) porosity in the soil macropore domain (PORp) was obtained by the difference between the saturated soil water content (TP) and the water content at the matric potential of -1 kPa, corresponding to pores with diameter larger than 300 µm; b) porosity in the soil matrix domain (PORm) was obtained by the water content at the matric potential of -1 kPa, corresponding to pores with a diameter smaller than 300 µm; c) air capacity in the soil matrix (ACm) was obtained by the water content at matric potential of -1 kPa subtracted from the water content at matric potential of -10 kPa; d) the indicator of soil water storage capacity (FC/TP) (dimensionless) was calculated using the ratio of the soil water content at FC and TP.

To verify if changes in soil physical properties occurred systematically in relation to the sampling positions, spectral analysis was used as described in Correchel et al. (1999). Additionally, the White test was used to assess whether the frequencies were significant ($p<0.05$) using SAS software (SAS, 2002).

For each of the variables, the average was calculated and comparisons between sampling positions at each depth were made through the confidence interval (85 %), following Payton et al. (2000). The decision criterion was that if the upper and lower limits of the average do not overlap, it was assumed that the averages of those populations were statistically and significantly different (Payton, 2000). All analyses were performed using SAS software (SAS, 2002).

RESULTS AND DISCUSSION

In the 0.0-0.1 m layer (Figure 2a), soil BD exhibited a lower value at the R position compared with IP and IR in most of the sampling points. These results corroborated Correchel et al. (1999) and Silva et al. (2014), who found lower BD values under NT in the crop row compared to the interrow. Soil mobilization during sowing and the presence of roots may have contributed to reduced BD at position R. Conversely, the absence of tillage and the cumulative traffic of machinery resulted in higher BD values along the transect at the IP and IR positions. Soil BD at the R position was lower than at the IP and IR positions (Table 1). This suggests that soil BD variations under NT occurred systematically along the corn rows and interrows according to whether furrows for seed and fertilizer placement were opened. These results are consistent with studies of Betioli Junior et al. (2012) and Silva (2003), which showed that opening furrows promoted soil disturbance restricted to the sowing rows and to a few centimeters from the furrows.

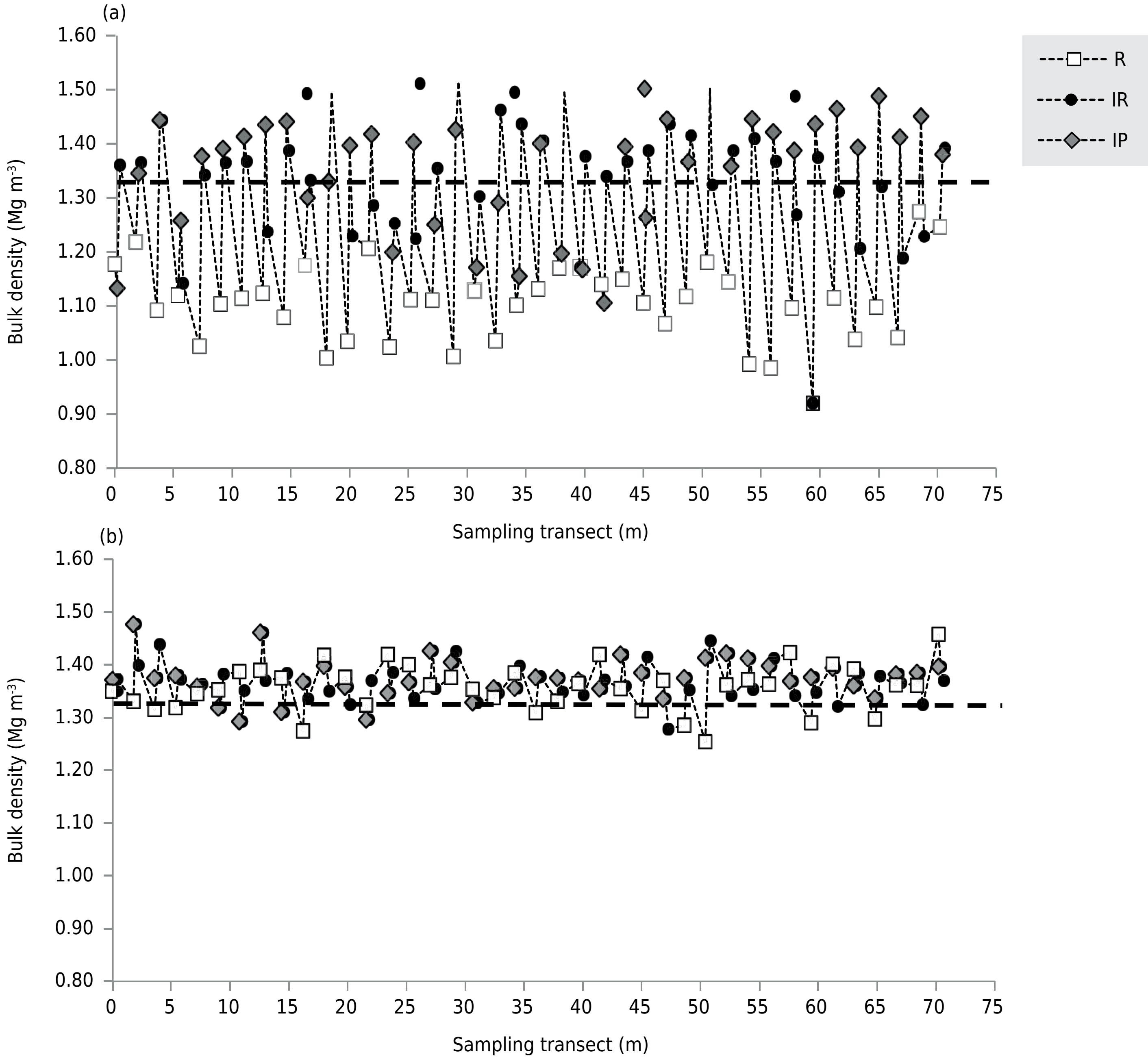

Figure 2. Soil bulk density (BD) variation in sampling positions along the transect and 0.0-0.1 m (a) and 0.1-0.2 m (b) layers, in the sampling positions at the row (R), interrow (IR) and intermediate position (IP). The dotted line represents the critical soil bulk density that restricts root growth (BDc-rest) equal to 1.32 Mg m^{-3}, obtained by Reichert et al. (2009) and Betioli Junior et al. (2012).

Soil bulk density has a close relationship with other soil properties that directly affect plant growth, such as aeration and resistance to root penetration (Correchel et al., 1999). The critical BD values for plant growth using the least limiting water range (BDc-LLWR) based on clay content of the soil were derermined by Reichert et al. (2009). The authors found that the BDc-LLWR of 1.25 Mg m^{-3} was the critical limit in a very clayey soil, with 750 g kg^{-1} of clay, in which restrictions or limitations to root growth of crops may be present. However, the same authors highlighted that the critical limit for BDc-LLWR did not necessarily reflect the NT restriction to root growth and, or, crop yield when the measured penetration resistance was at or above 2.0 MPa. Based on this observation, Reichert et al. (2009) proposed a critical BD that restricts root growth, called BDc-rest; for the soil of this study, BDc-rest = 1.32 Mg m^{-3}, which was in line with results obtained by Betioli Junior et al. (2012), who found the same value (1.32 Mg m^{-3}) in the same area under study using soil resistance to penetration of 3.5 MPa to calculate the LLWR. Using BDc-res = 1.32 Mg m^{-3}, the degree of compaction (DC) was calculated as the ratio between BD/1.32 Mg m^{-3}. The benefit of using DC is that it can be applied when comparing different soils, while using only BD values would result in unfair comparisons and erroneous interpretations. In the present study, DC at the R position in the 0.0-0.1 m layer was 83 %, with values ranging from 69.7 to 96.21 %. For the IP and IR, the average DC value was 102.3 %, with values ranging from 84.1 to 114.4 %. The lower DC values in the R position resulted from soil disturbance during seeding, as well as root mass in the soil at this sampling position.

We verified that about 70 % of samples at the IP and IR position had BD>1.32 Mg m^{-3} and DC>100 %. However, the R position did not exhibit any BD>BDc-rest, suggesting better soil physical conditions for root growth than at IP and IR in the 0.0-0.1 m layer. These better soil physical conditions at R will lead to higher water availability, increasing germination and plant establishment, which may contribute to greater crop yields. In the 0.1-0.2 m layer, the BD values were more homogeneous in the sampling transect (Figure 2b), as evidenced by the lower coefficient of variation (CV = 2.9 %) than in the 0.0-0.1 m depth layer (CV = 11.6 %) (Table 1). The greater heterogeneity of the BD in the upper soil layer may be explained by the effect of soil disturbance by the seeder,

Table 1. Average values and confidence intervals of soil physical properties at different sampling positions (R: crop row; IP: intermediate position between row and interrow; and IR: interrow) and soil layers

Soil property	R	IP	IR	CV
				%
		0.0-0.1 m		
Bulk density (Mg m^{-3})	1.103 ± 0.023	1.351 ± 0.033	1.347 ± 0.027	11.6
PORp (m^3 m^{-3})	0.085 ± 0.008	0.026 ± 0.007	0.019 ± 0.003	81.9
PORm (m^3 m^{-3})	0.509 ± 0.012	0.495 ± 0.010	0.504 ± 0.009	6.8
ACm (m^3 m^{-3})	0.139 ± 0.009	0.075 ± 0.011	0.065 ± 0.010	49.9
Field capacity (m^3 m^{-3})	0.371 ± 0.014	0.439 ± 0.008	0.420 ± 0.008	10.8
FC/TP	0.624 ± 0.021	0.811 ± 0.025	0.842 ± 0.021	15.8
		0.1-0.2 m		
Bulk density (Mg m^{-3})	1.357 ± 0.014	1.374 ± 0.012	1.365 ± 0.010	2.9
PORp (m^3 m^{-3})	0.013 ± 0.002	0.012 ± 0.001	0.013 ± 0.003	36.6
PORm (m^3 m^{-3})	0.520 ± 0.016	0.522 ± 0.017	0.514 ± 0.012	9.3
ACm (m^3 m^{-3})	0.067 ± 0.005	0.062 ± 0.004	0.071 ± 0.004	20.5
Field capacity (m^3 m^{-3})	0.453 ± 0.018	0.443 ± 0.018	0.460 ± 0.014	12.0
FC/TP	0.848 ± 0.012	0.859 ± 0.010	0.839 ± 0.011	4.3

CV: coefficient of variation; PORp: porosity in the soil macropore domain; PORm: porosity in the soil matrix domain; ACm: air capacity in the soil matrix; FC/TP: soil water storage capacity.

increased activity of roots, and wetting and drying cycles of the soil, which are more frequent and intense in this layer. In this study, the estimated furrow opening for sowing was approximately 0.12 m. Thus, layers deeper than 0.12 m are not affected by soil disturbance from the seeder. Therefore, differences in BD in the 0.1-0.2 m layer among the sampling positions were not detected. This lack of difference in BD among the sampling positions was observed throughout almost the entire transect for this layer. In the 0.1-0.2 m layer, about 92 % of the samples showed BD>1.32 Mg m^{-3}, and DC ranging from 94.7 to 112.1 %, confirming that soil disturbance for furrow opening affected BD only in the 0.0-0.1 m layer.

In the 0.0-0.1 m layer, the highest PORp values occurred at the R position (Table 1), with gradual reduction toward IR. These results suggested that outside the R position, there was reduction in the quantity of larger pores. This indicates that under R, there may be quick water drainage and air entrance after rainfall or irrigation compared to IR (Lanzanova et al., 2007). The infiltration rate was at its maximum in the corn row compared to the interrow, which is in line with the PORp results obtained in this study (Mohanty et al., 1996). There was no consensus on the optimal values for PORp, but it is important to establish fast air entry into the soil immediately after saturation (Reynolds et al., 2008). In the 0.1-0.2 m layer, the PORp values were similar among sampling positions, and were lower than those measured in the upper layer. These results suggest that furrow opening and the presence of corn roots did not increase the PORp. It should be noted that there was a substantial reduction in PORp values from the 0.0-0.1 to 0.1-0.2 m layer, which decreased about 84.7 % in R, while under IP and IR it declined 53.9 and 31.6 %, respectively.

Soil PORm did not differ among the positions and between soil layers (Table 1). Since total porosity is represented by the sum of PORp and PORm, the absence of tillage may result in a decrease in total porosity, mainly due to loss of larger diameter pores (>300 µm, PORp). The pores with larger diameters, occurring at R, may be more easily modified by soil compaction during traffic of agricultural machines. Moreover, Reynolds et al. (2002) reported that the largest PORm values found in soils under different textural classes were associated with higher organic carbon content, the presence of root channels, and biological activity. Similar results were obtained by Fidalski et al. (2008).

Soil ACm indicates the physical conditions for flow of gases in the soil and through the atmosphere interface. In the 0.0-0.1 m layer, the ACm at the R position had values around 1.86 and 2.14 times higher than at the IP and IR position, respectively. The negative gradient of ACm and PORp values toward IR suggests that there was a tendency for roots to be confined around the R position. The sum of the ACm values with PORp includes all macropores that are responsible for the free movement of air and water during the infiltration process (Reichert et al., 2007). Pore space is easily modified by soil compaction, and it is expected that properties that include these macropores would be more sensitive to changes resulting from furrow opening. The ACm was different between layers only at the R position, with the lowest values found in the 0.1-0.2 m layer. Machine traffic may cause damage to soil pores, leading to losses in the ACm domain porosity (Moreira et al., 2014). This effect can be seen in IP and IR in this study.

Soil FC and FC/TP ratio provides direct and quantitative estimates of soil water storage capacity in the root zone needed for crop growth (Reynolds et al., 2002). In this study, FC was used as an indicator of maximum water availability to plants. In the 0-0.1 m layer depth, FC had higher values in the IP and IR positions compared to R (Table 1), which was related to higher BD values in these positions. An increase in BD, followed by an increase in FC in a similar soil was also reported by Petean et al. (2010). These results were associated with reduction in macropores and, consequently, increased microporosity, generating pores with dimensions and geometry favoring capillary water retention (Portugal et al., 2008). However, greater soil water retention in IR and IP may not necessarily reflect benefits to the plant. With the increase in soil water retention, there is a concomitant decrease of air-filled porosity, which may reflect a greater proportion of BD>BDc-rest at these positions.

The ratio FC/TP around 0.66 indicates a good balance between soil water retention and aeration (1-FC/TP = 0.34) for plant growth was suggested by Reynolds et al. (2002). The FC/TP>0.66 indicates that soil aeration can become restricted at FC, leading to a negative impact on microbial activity and root respiration (Wendling et al., 2005). At the R position, the average FC/TP in the 0.0-0.1 m layer was close to the ideal value, with more than 80 % of the samples around 0.66 (Table 1). At the IR and IP positions, the FC/TP values were above 0.80, with 20 % of samples from the IR and absence of samples from the IP position close to 0.66. Thus, in order to allow suitable conditions of soil aeration and avoid water plant stress at the IR and IP positions, lower soil water content than FC was required. These results were confirmed by the amount of samples with BD>BDc-rest at the IP and IR positions, indicating that soil resistance to penetration and soil aeration may be limiting to plant growth. These values corroborate Reynolds et al. (2002) and Moreira et al. (2014), who also found FC/TP values near 0.80 under NT. In the 0.1-0.2 m layer, all FC/TP>0.66 suggests that in the 0.0-0.1 m layer, soil water storage increased from the R towards the IR position, and that soil water storage also increased from the 0.0-0.1 to 0.1-0.2 m layer. These changes in water retention at the sampling position result in poor soil aeration in interrows and in the 0.10-0.20 m layer.

The high values of BD, FC, and FC/TP found in this study can be attributed to the presence of two consecutive corn seasons in the same area prior to soil sampling. Additionally, there was a minimum number of species in the crop rotation over the years. Consequently, the crop in-row spacing and traffic occurred at the same location for at least two cropping seasons prior to soil sampling. In addition, soil and weather conditions in this area accelerate crop residue decomposition, favoring soil compaction by wheel pressure and leading to adverse conditions for plant growth in the soil physical environment. These results also indicate that the use of BD and Reynolds numbers have potential for identifying soil physical quality modification due to different sampling locations.

Values of BD, PORp, ACm, and FC reported in this study suggest that NT may induce soil conditions that lead to confinement of the plant root system in the 0.0-0.1 m soil layer around the crop rows. Thus, the roots are very likely to be restricted to a few centimeters from the R position, which may physically create an impediment to their development. Confinement of the plant root system can pose risks to plant development and reduce water and nutrient uptake, making the plants more vulnerable to environmental stresses. For example, in rainy years, outside the R environment, the plant may exhibit soil aeration limitations because soils with high BD tend to have slower water infiltration (Mohanty et al., 1996). However, in drier years, the presence of BD>BDc-rest can limit root growth by mechanical impedance. Moreover, the presence of high FC values at depth can act as a barrier to water infiltration, increasing soil water permanency, which can be beneficial to the crop during short periods of drought.

The results of spectral analysis of soil physical properties in the 0.0-0.1 m soil layer are in figure 3. The frequency is defined as the number of times that one cycle occurs per unit of distance. When this value was significant, data variability exhibited systematic behavior, i.e., repeated behavior in a determined distance interval. In the 0.0-0.1 m soil layer, the frequency peaks for the BD, PORp, and ACm, and FC/TP parameters occurred at a frequency of 0.078 cycles m^{-1} when the R position was compared to IP and IR positions, which were significant by the White test ($p<0.05$). FC was only significant in the R-IR comparison. Considering that the sampling transect was 72 m, this frequency was equal to 1.80 m (distance between rows where soil samples were taken), i.e., there was a cycle that was repeated every 1.80 m, confirming that for this soil, physical properties exhibited a systematic behavior related to the corn R and IR. Similar results were reported by Correchel et al. (1999) under the NT system, indicating that the peak of BD was located at the frequency corresponding to the distance between the corn rows in the sampling transect. The variable PORm did not show dependence on the sampling position, indicating that for future evaluation of PORm, samples can be taken from any position, regardless of the crop row. The PORm was influenced by management practices and soil organic C content variability (Reynolds et al., 2002).

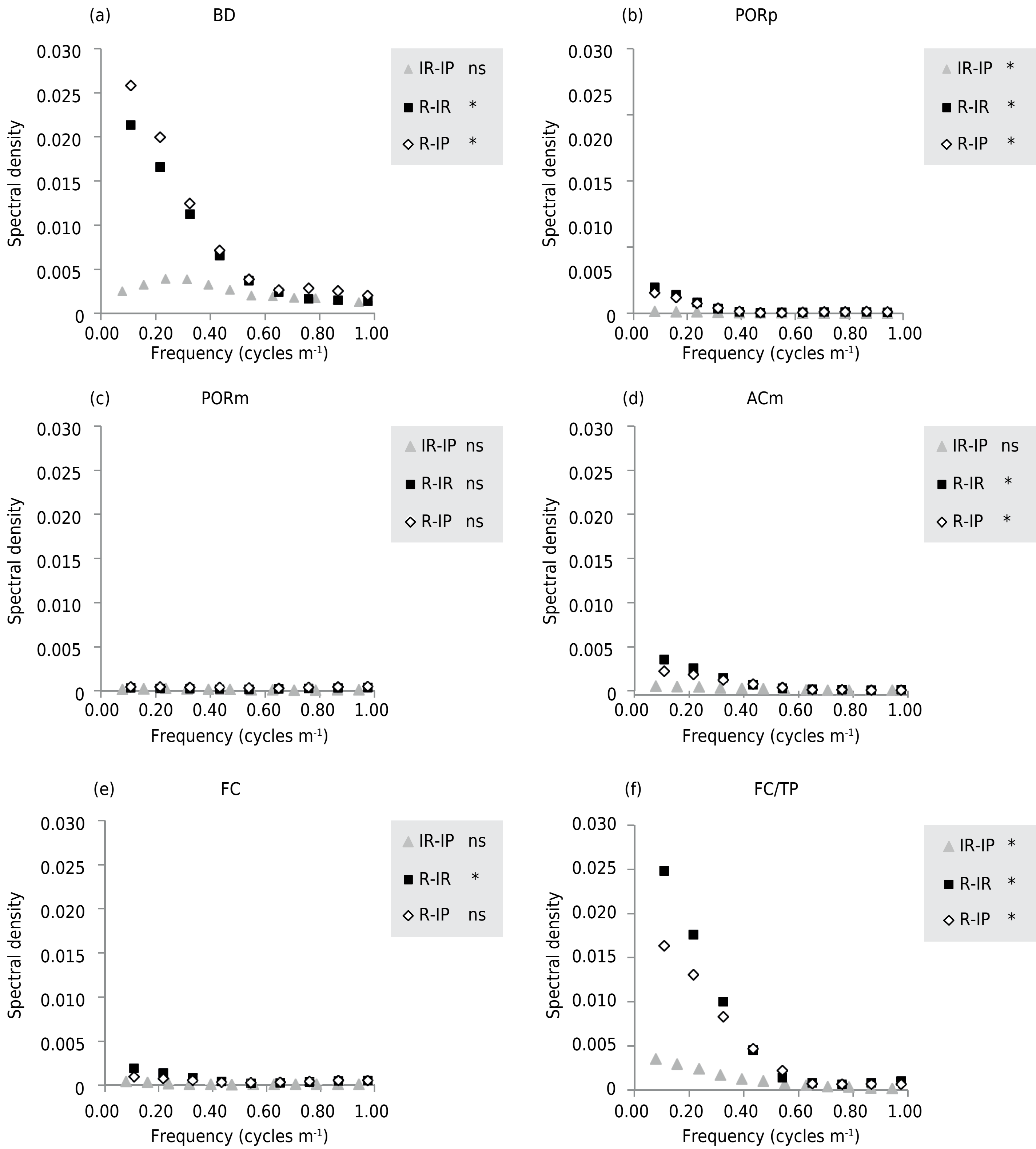

Figure 3. Spectral density of soil physical properties: (a) soil bulk density (BD); (b) porosity in the soil macropore domain (PORp); (c) porosity in the soil matrix domain (PORm); (d) air capacity in the soil matrix (ACm); (e) soil field capacity (FC); and (f) soil water storage capacity (FC/TP), comparing the sampling positions in the 0.0-0.1 m layer. * and ^{ns}: significant and non-significant, respectively, at 5 % (White test).

Comparison between positions IR-IP revealed that the frequency was significant only for PORp and FC/TP soil properties, showing that the effect of the furrow opening influenced the IP position. The properties BD, PORm, ACm, and FC showed no systematic difference between the IR and IP position, indicating that the effects of opening furrows were located in the upper soil layer (0.0-0.1 m) and did not significantly affect soil physical properties beyond the R position. In the 0.1-0.2 m layer, the frequency did not differ among the sampling positions, indicating that the behavior of soil physical properties did not depend on sampling position. These results suggest that sampling can be carried out in the 0.1-0.2 m layer at any point in the field. Results also indicate that the mechanisms that affect the BD, PORp, ACm, FC, and FC/TP properties at the R position in the 0.0-0.1 m layer, had no influence on the 0.1-0.2 m layer, meaning that the tillage effect was restricted to the surface layer. Thus, for studies using soil sampling, aiming to quantify soil physical properties in NT, it is necessary to take the sampling position only in the 0.0-0.1 m layer into account.

Soil physical properties showed different behavior among the sampling positions in the 0.0-0.1 m layer. The R presented better soil physical conditions for plant growth compared to the IP and IR positions. The effects of soil disturbance in crop rows significantly modified soil porosity, especially pores with a diameter>300 µm, in agreement with the findings of Silva et al. (2014) and Betioli Junior et al. (2014). There were no disturbance effects below the 0.1 m depth. In the 0.1-0.2 m layer, soil physical limitation related to soil aeration may happen under wetter conditions. Furthermore, soil water retention increased in the 0.1-0.20 m soil layer, suggesting it was functioning as a barrier to water infiltration. Our findings suggest that, in this soil under NT, soil physical conditions may result in roots being concentrated or confined to a few centimeters around the crop row both horizontally and vertically. Future studies of soil physical properties under NT should consider sampling position, and specifically take the crop row in the 0.0-0.1 m layer into account.

CONCLUSIONS

The sampling positions have a systematic variation of the soil physical properties under no-tillage system, with the exception of porosity in the soil matrix domain (PORm). There was no difference for soil physical properties between sampling positions in the 0.1-0.2 m layer.

Improved soil physical conditions for soil bulk density, porosity in the soil macropore domain, air capacity in the soil matrix, and soil water storage capacity were found in the row (R) position in the 0.0-0.1 m layer.

The assessment of soil physical parameters under NT should consider the sampling position with regard to crop rows.

ACKNOWLEDGMENTS

Thanks to the CNPq and CAPES for financial support.

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