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ABSTRACT

There is no consensus regarding seasonal changes in soil physical properties within and between rows in long-term no-till (NT) crop production systems. We hypothesized that soil physical properties in a Rhodic Ferralsol under long-term NT differed within and between rows and that these changes are influenced by wetting and drying cycles (WDC). Undisturbed samples were taken within and between crop rows from layers of 0 to 0.10 and 0.10 to 0.20 m depth in September 2010, 2011 and 2012 and March 2012 and 2013. At the first sampling, 40 soil samples were collected within the maize (*Zea mays* L.) row (R), at interrow (IR) sampling positions, and at an intermediate position (IP) between R and IR. Coordinates for each sampling point were identified so that subsequent samples could be collected from the same location. Soil bulk density (Db), soil water retention curve (WRC), S index, air-entry pressure and pore size distribution were determined. The results confirmed that furrow opening causes significant positive changes in soil physical properties within the crop row and plant growth can be affected by the "confinement" of roots within the R position within long-term NT sites. With each successive sampling, Db decreased and was significantly influenced by recent WDC. The pore size distribution showed larger pores with each successive sampling, providing a higher S index, air-entry pressure, and improved soil physical quality over time. The steady state of soil structural conditions achieved at long term NT can be affected by short term influences related to the crops and weather conditions. However, soil physical properties indicated that a new equilibrium was achieved and that soil under long-term NT may remain physically functional. Our results confirm that soil physical properties under NT are highly dynamic and strongly influenced by (i) soil disturbance caused by furrow opening, (ii) wetting and drying cycles, and (iii) sampling depth. Therefore, we recommend that for quantifying soil physical quality within no-till fields, measurements should be taken within and between crop rows.

1. Introduction

No-till (NT) is a conservation tillage practice where crops are grown without primary tillage (e.g., moldboard plowing, chisel plowing, or disking), although there is a soil disturbance due to opening of furrows during sowing. The NT system can be effective in reducing erosion, maintaining soil surface cover by plant residues, and lowering energy needs (Lal et al., 2007). Reduced working time and lower costs are additional reasons for adopting NT (Soane et al., 2012).

Currently there is a lack of knowledge regarding seasonal dynamics of soil physical and structural properties under NT. Understanding these changes, including the spatial variability, is important for improving management decisions. Most field studies do not take into account row and interrow management zones, so samples are normally taken only between crop rows (*i.e.*, in the interrow). However, furrow opening is a mechanical soil disturbance in NT that modifies the soil physical environment in and near the crop rows. The furrow openers can reach up to around 0.10 m depth and promote a local relief of the superficial soil compaction (da Silva et al., 2014; Nunes et al., 2015). Mohanty et al.

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(1996) showed that water infiltration rate was highest in crop rows, while da Silva et al. (1997) reported soil physical differences between row and inter-row zones. Tormena et al. (2008) also found better soil physical quality within crop rows. What appears to be unknown is how soil physical properties change with lateral distance from the crop row due to both the intensity of soil disturbance by furrow opening and plant root growth.

Seasonal changes in soil physical properties are crop-specific and are generally attributed to factors including overall tillage operations (Osunbitan et al., 2005), soil disturbance beneath crop rows under NT (da Silva et al., 1997), occurrence and intensity of machinery traffic (Ahmad et al., 2009), changes in soil organic matter (Scott and Wood, 1989), cumulative rainfall after tillage (Busscher et al., 2002), activity of earthworms and other soil organisms (Yvan et al., 2012), occurrence of wetting-drying cycles (Silva et al., 2012; Pires et al., 2008; Bodner et al., 2013), crop rotation (Sasal et al., 2010) and intercropping (Chioderoli et al., 2012). Data from a single sampling only indicates the physical soil condition at a specific sampling time.

Crops have different types of root systems and are sown with different row spacings. Therefore, in addition to differences due to opening of planting furrows, each crop can also cause changes in soil physical conditions. Głąb et al. (2013) evaluated effects of crop rotations on the soil pore system and showed that each system affected soil porosity differently. Soil porosity differences were also observed by Sasal et al. (2010) who compared soybean [*Glycine max* (L.) Merr.], maize and wheat (*Triticum aestivum* L.). Soil disturbance from seeding operations can result in “localized tillage” of the soil surface under NT (da Silva et al., 1997, 2014) and thus impact soil physical quality. Usually it has been considered that stabilization of soil properties is reached after about five years of continuous NT (VandenBygaart et al., 1999; Rhoton, 2000; Alvarez et al., 2009). However, short-term changes in soil physical properties may be driven by different factors such as agricultural machinery, soil type, topography, climate and crop selection (Strudley et al., 2008). Evaluating seasonal soil physical changes may provide a better understanding of soil physical functioning under NT and help to define management strategies that will create the least limiting soil physical conditions for plant growth.

Soil physical resilience, defined as the intrinsic ability of a soil to recover from stresses and return to a new equilibrium similar to its previous state (Seybold et al., 1999), is a key component of soil physical quality. Several regenerative processes determine soil physical resilience, including growth and activity of roots, shrink-swell processes driven by wetting-drying cycles (WDC) and activity of soil organisms (Gregory et al., 2007). In field experiments, Peng et al. (2007) and Bodner et al. (2013) showed that WDC resulted in increased soil macroporosity. In Brazilian soils, Bavoso et al. (2012) found that WDC helped recover soil air permeability after mechanical stress (compaction). Pires et al. (2005, 2008) also showed that increasing WDC increased soil porosity, specifically pores ranging from 10 to 500 μm, and that most important changes occurred during the first three WDC.

We hypothesized that: (i) changes on soil physical properties in a Rhodic Ferralsol under long-term NT are a function of the positions relative to the rows and interrows of the crop, and (ii) these changes are influenced by WDC resulting from the natural variability in rainfall followed by drying. Therefore our objectives were to quantify bulk density (Db), soil water retention curve (WRC), S index, air-entry pressure and the soil pore size distribution along five successive samplings within rows, interrows and at an intermediate position between the row and interrow sampling sites.

2. Material and methods

2.1. Soil sampling

Samples were taken from a field on a commercial farm in Maringa, State of Paraná (23° 30′ S, 51° 59′ W; 454 m asl), Southern Brazil. The investigation site has an annual average temperature of 22 °C and precipitation of 1450 mm. The dominant climate type is Cfa (mesothermal humid subtropical). The soil was classified as Rhodic Ferralsol (WRB, 2006). Particle size analysis indicated 790 g kg^{-1} of clay, 90 g kg^{-1} of silt and 120 g kg^{-1} of sand within the 0 to 0.10 m depth and 800 g kg^{-1} of clay, 50 g kg^{-1} of silt and 150 g kg^{-1} of sand within the 0.10–0.20 m depth. Soil organic carbon did not differ ($p > 0.05$) between successive samplings with values ranging from 1.98 to 2.23 and 1.28 to 1.45% within the 0 to 0.10 and 0.10 to 0.20 m layers, respectively.

This area has been under NT since 1980 and was cropped with soybean and second-crop maize (or maize + *Brachiaria brizantha*) at the time of sampling. Fertilizer was applied at sowing using a seeder/fertilizer with front cutting discs and parabolic tines at a

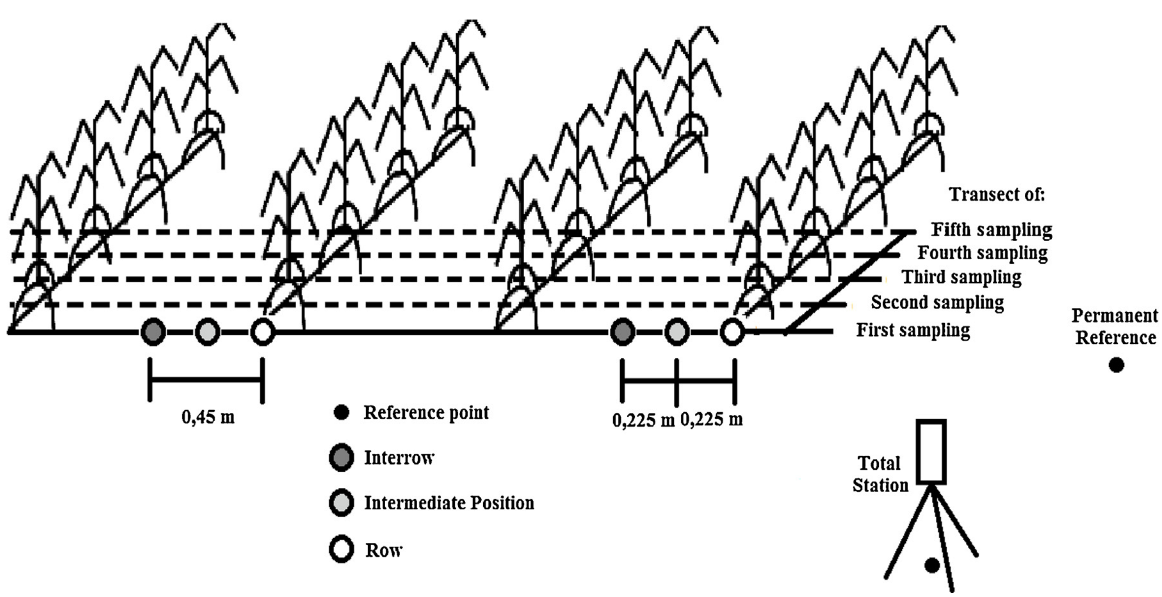

Fig. 1. Illustration of the transect and sampling sites established within the experimental area.

cutting angle of 20°, a rod thickness of about 30 mm and a penetration depth of between 0.10 and 0.12 m. Fertilizer and pesticides for control of insects, diseases and weeds were applied according to the specific recommendations for each crop. The number of field operations involving tractors (total mass 4122 kg), seeders (total mass 2300 kg), sprayers (total mass 450 kg) and harvesters (total mass 7.000 kg) varied according to crop. Within the sampling area, machinery traffic was performed completely at random. Crop yields were above average for the region, with maize and soybean yields averaging approximately 7430 and 3400 kg ha^{-1}, respectively. More details about the site and soil physical characteristics previous to the samplings are described in da Silva et al. (2014).

Sampling was carried out in September after harvesting maize that was grown with a row spacing of 0.90 m, and in March after harvesting soybean that was grown in 0.45 m rows. A transect of approximately 72 m was established perpendicular to the maize rows, along which, 120 sampling positions were selected: 40 in-row (R), 40 interrow (IR), and 40 intermediate positions (IP) between R and IR positions. All sampling positions were set up using a total station—Leica® TC 407 (Leica Geosystems AG, 2008) with a maximum error of 0.005 m. The IR and IP positions were 0.45 and 0.225 m away from the R positions in maize (Fig. 1). For subsequent campaigns (*i.e.*, 2nd in September 2011, 3rd in March 2012, 4th in September 2012, and 5th in March 2013) samples were taken at the re-located positions just a few centimeters away from the initial sampling location.

The first sampling was performed in September 2010 after two consecutive maize crops. The fourth sampling was performed after growing brachiaria (*Brachiaria brizantha*) as an interseeded cover crop between the maize rows. For this study, the same seeder was used for sowing soybean and maize. Soybean and corn were grown with a row spacing of 0.45 m (plant spacing of approximately 0.07) and 0.90 m (plant spacing of approximately 0.18 m), respectively. The direction of the seeding rows was always the same, although there were slight variations in the distance between external furrows of two parallel field passes among seedings. Therefore, the distance between rows was not exactly the same for all crops. However, the samplings were carried out in points previously demarcated to identify the sampling position (R, IR or IP) at the sampling time.

Undisturbed soil samples were collected from the 0 to 0.10 m and 0.10 to 0.20 m layer using cores with an inner diameter of 0.075 m and a height of 0.05 m. The cores were introduced slowly and continuously by an electro-mechanical sampler to ensure structural integrity of the soil. After each sampling, soil cores were wrapped in aluminum foil and taken to the laboratory.

2.2. Soil analysis

The samples were prepared by removing excess soil, so the volume would be exactly that of the cylinder. The samples were saturated for 48 h by gradually raising the water level in a tray up to approximately two thirds the height of the cores.

The soil water retention curve (WRC) was determined using an adaptation of the evaporation method (Schindler and Müller, 2006). Saturated samples were subsequently dried in a room with a controlled temperature of 25 °C while measuring water potential (Ψ) and water content (θ) continuously. The Ψ was determined using T5 tensiometers (UMS GmbH München, 2009) for the range $0 > \Psi \geq -80$ kPa, while the $\Psi < -80$ kPa was determined using a psychrometer [model *Dewpoint PotentiaMeter*—WP4-T (Decagon Devices, 2007)]. WP4-T measures Ψ with an accuracy of ±100 kPa (Decagon Devices, 2007) then the determinations were done below −500 kPa, according to Ojeda et al. (2013) and Mollinedo et al. (2015). The parameters of van Genuchten (1980) equation fitted to WRC data were analyzed to know if this strategy was adequate. The tensiometers had porous ceramic cups 0.5 cm in diameter that were 0.6 cm in length and had a 6 cm acrylic glass shaft that was connected to the sensor body. To determine Ψ with tensiometers, two readings (close to center of the soil core and the horizontal distance between tensiometers was 0.02 m) were obtained within each sample and averaged: one at a depth of 0.013 m and the other at 0.038 m. A reading of soil water potential was taken when variation of Ψ was at most ±0.1 kPa per minute (this equilibrium time can be higher under dry soil conditions). Immediately after determining Ψ, the samples were weighed to determine soil water content. To determine soil bulk density (Db) and soil water content, the samples were dried at ±105 °C for 24 h. Db (Mg m^{-3}) was calculated according to Grossman and Reinsch (2002).

Soil porosity was classified according to the pore diameter obtained from the WRC. Mean pore radius was calculated as suggested by Lal and Shukla (2004). Pores with a diameter ≥50 μm were considered "macropores" (pores that drain at $\Psi = -6$ kPa) and those with a diameter of <50 μm "micropores" (water retained at $\Psi = -6$ kPa), as suggested by Reichert et al. (2009a).

The van Genuchten (1980) equation was fitted to WRC data (tensiometers and dewpoint potentiometer data were used simultaneously) by simultaneously computing the parameters θs, θr, α and n. The parameter m was assumed to equal (1–1/n). The field capacity (FC) or water content at −10 kPa and wilting point (PWP) or water content at −1500 kPa were calculated using the fitted WRC. Plant available water content (PAWC) was assumed to be the amount between FC and PWP.

Pore size distribution was computed using the first derivative of the fitted van Genuchten (1980) equation (Eq. (1)):

$$d\theta/dh = -mn(\theta s - \theta r)(\alpha^n)h^{(n-1)}/(1 + (\alpha h)^n)^{(m+1)} \quad (1)$$

where $d\theta/dh$ is the first derivative of WRC; θr is the residual water content ($m^3\,m^{-3}$); θs is the saturated water content ($m^3\,m^{-3}$); h is the pressure head in kPa; α, n,m are parameters defining the van Genuchten curve.

The WRC slope at the inflection point (*i.e.*, the S index) was calculated as proposed by Dexter (2004):

$$S = -n(\theta s - \theta r)[(2n - 1)/(n - 1)]^{[(1/n)-2]} \quad (2)$$

2.3. Statistical analysis

Statistical analyses were performed using a SAS statistical package (SAS Institute, 2002). Initially, homoscedasticity of Db data was evaluated using Levene's test ($p > 0.05$). A Spearman correlation was used to assess the degree of dependence of Db for samples collected from the same point at different times. Comparisons of Db among field positions and sampling times as well as their interactions were performed using the Proc mixed procedure ($p < 0.05$) available in SAS Institute (2002). The Proc mixed repeated statement was used to take into account spatial dependence according to SAS Institute (2002). Means comparison were done based on differences in the least square means using Tukey-adjusted P > t values. The functional dependence between WDC and Db was evaluated using the Proc Reg procedure ($p < 0.05$) available in SAS Institute (2002). In this study, rain events >20 mm followed by the occurrence of a minimum of three dry days without rainfall were considered a WDC, as previously established by Silva et al. (2012). The 120 sampling positions were separated in nine possible sequences of positions (IR → IR, IR → R, IR → IP, R → IR, R → R, R → IP, IP → IR, IP → R, IP → IP) based on the positions identified at first and second sampling, then the percentage of it sequence and Db were determined. The same procedure based on

Table 1
Adjusted parameters for comparison of the water retention curve.

	Model	θs					θr					α					n				
Complete model	w0	θs_1	θs_2	θs_3	θs_4	θs_5	θr_1	θr_2	θr_3	θr_4	θr_5	α_1	α_2	α_3	α_4	α_5	n_1	n_2	n_3	n_4	n_5
1 parameter in commom	w1	θs					θr_1	θr_2	θr_3	θr_4	θr_5	α_1	α_2	α_3	α_4	α_5	n_1	n_2	n_3	n_4	n_5
	w2	θs_1	θs_2	θs_3	θs_4	θs_5	θr					α_1	α_2	α_3	α_4	α_5	n_1	n_2	n_3	n_4	n_5
	w3	θs_1	θs_2	θs_3	θs_4	θs_5	θr_1	θr_2	θr_3	θr_4	θr_5	α					n_1	n_2	n_3	n_4	n_5
	w4	θs_1	θs_2	θs_3	θs_4	θs_5	θr_1	θr_2	θr_3	θr_4	θr_5	α_1	α_2	α_3	α_4	$\alpha 5$	n				
2 parameters in commom	w5	θs					θr					α_1	α_2	α_3	α_4	α_5	n_1	n_2	n_3	n_4	n_5
	w6	θs					θr_1	θr_2	θr_3	θr_4	θr_5	α					n_1	n_2	n_3	n_4	n_5
	w7	θs					θr_1	θr_2	θr_3	θr_4	θr_5	α_1	$\alpha 2$	$\alpha 3$	$\alpha 4$	$\alpha 5$	n				
	w8	θs_1	θs_2	θs_3	θs_4	θs_5	θr					α					n_1	n_2	n_3	n_4	n_5
	w9	θs_1	θs_2	θs_3	θs_4	θs_5	θr					α_1	α_2	α_3	α_4	α_5	n				
	w10	θs_1	θs_2	θs_3	θs_4	θs_5	θr_1	θr_2	θr_3	θr_4	θr_5	α					n				
3 parameters in commom	w11	θs					θr					α					n_1	n_2	n_3	n_4	n_5
	w12	θs					θr					α_1	α_2	α_3	α_4	α_5	n				
	w13	θs					θr_1	θr_2	θr_3	θr_4	θr_5	α					n				
	w14	θs_1	θs_2	θs_3	θs_4	θs_5	θr					α					n				
4 parameters in commom	w15	θs					θr					α					n				

1, 2, 3, 4 and 5 after θs, θr, α and/or n means the sampling done in September 2010, September 2011, March 2012, September 2012 and March 2013, respectively.

second to third, third to fourth and fourth to fifth were repeated. For example, the second sampling within sequence of IR → IR in first to second and second to third not presented the same mean, because the sampling points showed spatial position changes in successive samplings and Db and percentage were determined according to nine possible sequences of positions for each sequence of sampling independently.

Statistical comparisons between van Genuchten parameters from different samplings was carried out using procedures described in Carvalho et al. (2010), with the likelihood ratio test ($p < 0.05$). This method tested the following hypotheses: (a) the van Genuchten parameters are equal in successive samplings; and (b) one or more van Genuchten parameters are different in successive samplings. Through this method, equations are adjusted with the independent (each sampling has a value for parameter) or common (all samplings has same parameter value) parameters in the samplings and residual errors ($p < 0.05$) of equations were tested against common model (four parameters in common—Table 1). The best model was chosen based on the smallest square root of the normalized mean squared error.

3. Results and discussion

3.1. Bulk density

Db values for sampling positions and layers at different sampling dates are shown in Fig. 2. Within the 0–0.10 m layer, Db was much smaller ($p < 0.05$) in R than IP or IR positions, while within the 0.10 to 0.20 m layer there were no significant differences between sampling positions ($p > 0.05$). The smallest Db values in the R position within the 0–0.10 m layer (about 1.00–1.10 Mg m^{-3}) indicated a physical environment with minimal restriction to root growth. However, this thin layer with low Db overlies a layer with high Db that may limit crop development under dry weather conditions.

In a previous study at the same area, Betioli et al. (2012) found that the reference bulk density (Dbref) obtained using a standard Proctor test for this soil was 1.52 Mg m^{-3}. Based on that value, the relative bulk density (RDb = Db/DbRef) or "Degree of Compactness" (DC) within the R position at the initial sampling was 0.72 within the 0 to 0.10 m layer. While at IR and IP positions within the 0 to 0.10 m layer and at all sampling positions within the 0.10–0.20 m layer the DC values were between 0.89 and 0.90. With the exception of the R position, DC values during the first sampling were higher than 0.86, which was suggested by Suzuki et al. (2007) as the limiting value for crops grown. Plant growth may be affected by "confinement" of plant roots to within the R position especially during drier weather conditions when soil water potential and soil resistance to penetration may limit root growth or during excessively wet weather when soil aeration may limit root growth within interrow areas. For subsequent samplings, DC values were lower than 0.87 in both layers and at all positions, suggesting that after the first two maize crops (initial sampling) NT was improving soil physical quality.

The mean values of Db within the 0–0.10 m layer at the R position were significantly different between the first and fourth samplings. Db at the IP position was higher than the other positions only in the first sampling. At the IR position, Db decreased from the first to the fourth sampling and Db values at the second and third sampling were not different from the fifth sampling. However, the fourth sampling had significantly lower Db values. Among successive samplings within the 0.10–0.20 m layer,

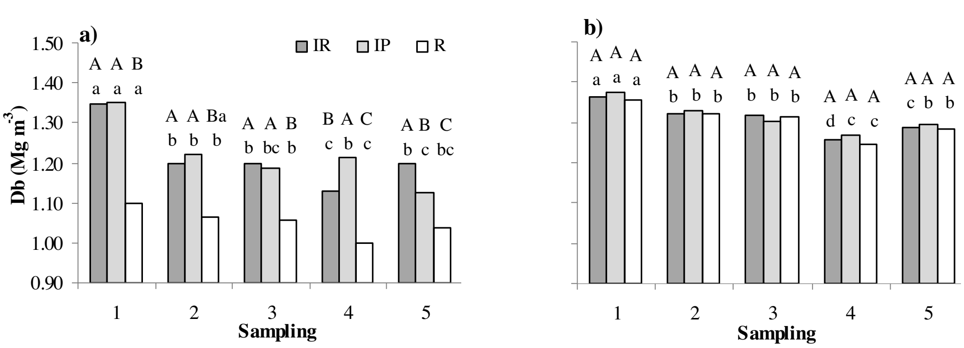

Fig. 2. Bulk density (Db) for interrow (IR), intermediate position (IP) and row (R) at 0–0.10 (a) and 0.10–0.20 m (b). Capital letters are used to compare positions within each sampling and lower case letters to compare sampling date within each position. Means followed by the same letter are not significantly different at the $p < 0.05$ level.

Table 2
Percentage of samples in the interrow (IR), intermediate position (IP) and row (R) and spatial position changes (%) in different sampling time.

Position	First	Second	Third	Fourth	Fifth
IR	33.33	30.83	43.33	33.33	44.17
IP	33.33	41.67	29.17	48.33	6.67
R	33.33	27.50	27.50	18.33	49.17
Changes between sampling Positions		First to second	Second to third	Third to fourth	Fourth to fifth
IR → IR		20.00	7.50	12.50	7.50
IR → R		5.83	11.67	9.17	25.00
IR → IP		7.50	11.67	21.67	0.83
IP → IR		6.67	21.67	10.00	30.83
IP → R		3.33	8.33	4.17	14.17
IP → IP		23.33	11.67	15.00	3.33
R → IR		4.17	14.17	10.83	5.83
R → R		18.33	7.50	5.00	10.00
R → IP		10.83	5.83	11.67	2.50

Table 3
Spearman correlations for Db between the five samplings for the 0 to 0.10 m and 0.10 to 0.20 m layers.

Sampling	0–0.10 m				0.10–0.20 m			
	Second	Third	Fourth	Fifth	Second	Third	Fourth	Fifth
First	0.43*	−0.13^{ns}	0.46*	0.08^{ns}	0.11^{ns}	0.20^{ns}	0.15^{ns}	0.21^{ns}
Second		0.08^{ns}	0.41*	0.09^{ns}		0.02^{ns}	0.00^{ns}	0.04^{ns}
Third			−0.08^{ns}	0.02^{ns}			0.06^{ns}	0.00^{ns}
Fourth				0.04^{ns}				−0.06^{ns}

^{ns}not significant; *significant at the 0.05 level.

Db in the first sampling was statistically ($p < 0.05$) the highest, while in the fourth it was lowest for all three positions. During the second, third and fifth samplings, Db values were similar and statistically intermediate between the first and fourth samplings. The only difference between three positions in Db behaviour within the 0.10–0.20 m layer was that the fifth sampling was lower than the third at the IR position, while at the IP and R positions, Db was similar at the third and fifth samplings.

Differences in Db indicated that significant short term changes may occur, especially within the 0 to 0.10 m layer. These results agree with Osunbitan et al. (2005) who showed weekly changes in Db and suggested that the absence of vegetal cover and exposure of the soil surface to direct impact of rainfall may be responsible for these changes. In contrast, Silva et al. (2012) showed that chiselling soils previously under NT reduced Db, but within six months after disturbance Db once again increased to a point where no further effects were observed. Alletto and Coquet (2009) reported that under conservation tillage Db at 0.15 m depth remained quite stable throughout the growing season.

To explain Db reductions, we assessed the variation within sampling positions from one crop to the next to determine if there was a “residual effect” due to the plant row, soil disturbance and root activity. The results showed small variation between the first and second samplings, even though 38.3% of the positions were not repeated (Table 2). For the second to third, third to fourth and fourth to fifth samplings 73.3%, 67.5% and 79.2% of the positions were not repeated, respectively. The results were different, possibly because the third and fifth samplings followed soybean that was planted in 0.45 m rows compared to maize that was planted in 0.9 m rows. For the entire experiment, 79% of the sampling points were identified as R, but only 3.3% had that designation in all samplings. Further examination of the 79% showed that about half were associated with the soybean crop (third and fifth samplings). These results suggest that in successive samplings the relative positions of R and IR do not tend to be spatially repeated.

Spearman correlations (Table 3) were used to describe possible influences of one sampling on successive ones. Within the 0 to 0.10 m layer, there was a significant correlation between samples taken after maize (first, second and fourth samplings). These results suggest that when crops with similar spacing are grown, the relative positions of R and IR tend to be spatially repeated. Significant relationships were not observed in samplings after soybean (*i.e.*, third and fifth sampling), because the narrower row spacing (0.45 m) resulted in large proportional changes among R, IP and IR positions. Within the 0.10 to 0.20 m layer, Spearman

Table 4
Changes in bulk density (Db, Mg m^{-3}) between two consecutive samplings (first to second; second to third; third to fourth; fourth to fifth) for the possible sequences of positions (IR → IR, IR → R, IR → IP, R → IR, R → R, R → IP, IP → IR, IP → R, IP → IP) at 0–0.10 m layer.

Changes between sampling Positions	First to second			Second to third			Third to fourth			Fourth to fifth		
IR → IR	1.36	→	1.20	1.22	→	1.14	1.17	→	1.14	1.10	→	1.23
IR → R	1.28	→	1.14	1.17	→	1.05	1.26	→	1.01	1.14	→	1.02
IR → IP	1.37	→	1.18	1.22	→	1.19	1.19	→	1.19	1.15	→	1.22
R → IR	1.13	→	1.18	1.07	→	1.22	1.05	→	1.15	0.98	→	1.18
R → R	1.10	→	1.03	1.01	→	1.05	1.06	→	1.00	1.02	→	1.10
R → IP	1.09	→	1.19	1.10	→	1.17	1.06	→	1.23	0.99	→	1.12
IP → IR	1.31	→	1.21	1.20	→	1.21	1.21	→	1.09	1.21	→	1.19
IP → R	1.43	→	1.10	1.24	→	1.06	1.19	→	0.99	1.21	→	1.02
IP → IP	1.35	→	1.25	1.25	→	1.20	1.17	→	1.24	1.29	→	1.10

IR: interow position; R: row position; IP: intermediate position (IP). Changes in Db at 0.10–0.20 m was not shown because there were no changes between positons.

correlations between samplings were not significant, suggesting that Db changes between R and IR positions were restricted to the surface layer.

We hypothesized that a residual effect due to soil disturbance at sowing could have reduced Db within IR and IP positions. However, when analyzing Db for samples that were previously in an R position, Db increased in subsequent sampling (Table 4). Therefore, Db values for the IR and IP positions that were R positions in the previous sampling did not differ from the mean of the IR and IP sites (Fig. 2).

These results suggest that Db reductions due to soil disturbance at sowing were not persistent. Soil mobilization within the 0–0.10 m layer due to mechanical disturbance at sowing and seminal root development had only a short term residual effect. Alleto and Coquet (2009) also found that changes in Db could be detected for less than five months after sowing, but in general, there are very few published studies that thoroughly describe temporal effects of furrow openers on soil physical condition. In contrast, other studies have shown that temporal changes in Db can be detected for six months (Silva et al., 2012) to one year (Calonego and Rosolem, 2010; Leão et al., 2014) after chiseling previous NT sites.

We found a consistent reduction in Db at the R position when samples from IP and IR positions became R position (IR → R and IP → R) in the subsequent sampling (Table 4). Soil disturbance due to furrow opening and subsequent root development presumably contributed to maintaining lower Db values until the next sampling. Sowing was performed immediately after sampling for maize (March) and a month after sampling for soybean crop (September). Therefore, there were five or six-month intervals between sowing and the next sampling. The smaller Db values at the R position five or six-months after sowing indicate that there was a short term (less than one year) residual effect.

3.2. Relationship between bulk density and wetting drying cycles

Temporal changes in Db appear to be related to the influence of wetting and drying cycles (WDC). Håkansson (2005) stressed that the intensity and frequency of WDC can increase porosity, mainly within surface layers. As previously established by Silva et al. (2012), events with more than 20 mm rainfall followed by a minimum of three dry days were considered as the criteria defining a WDC. Plant available water capacity at this site was

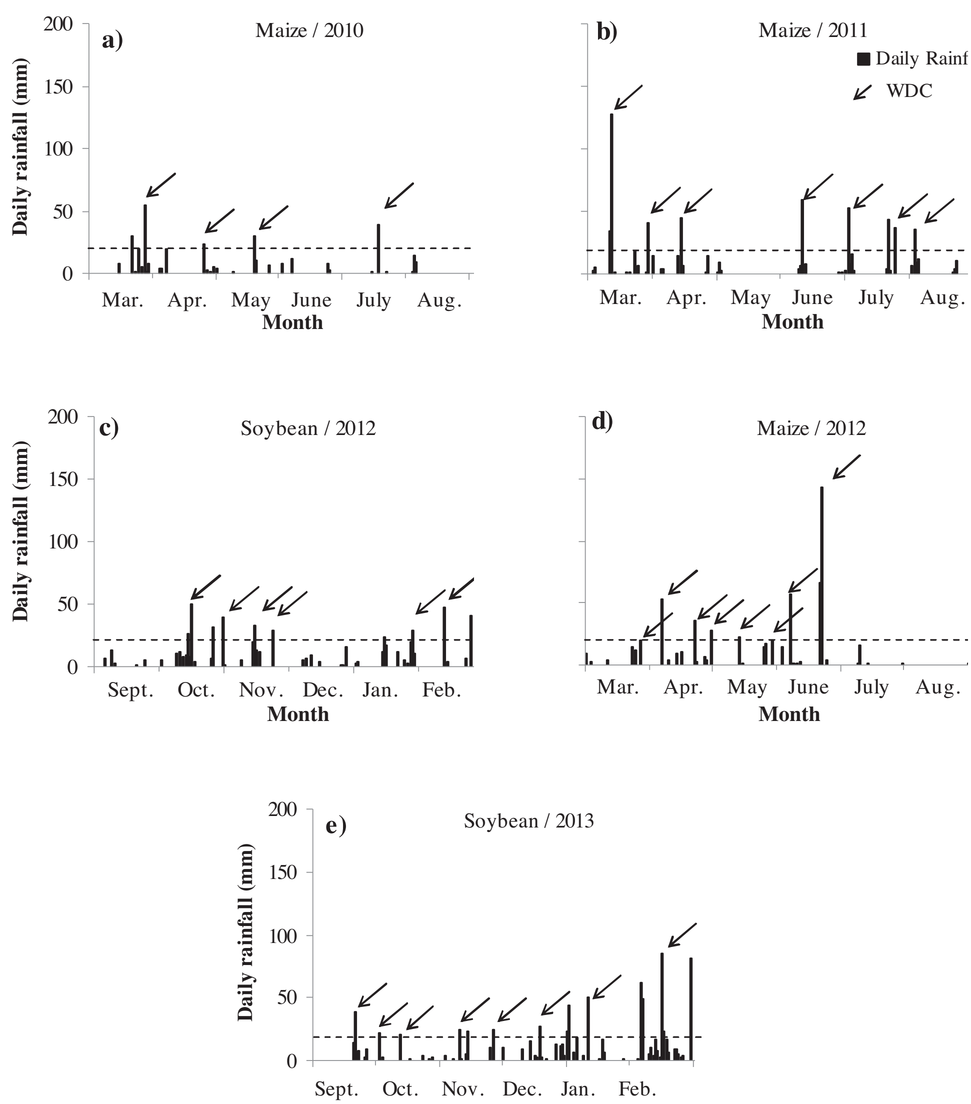

Fig. 3. Daily rainfall between March and August 2010 (a), March and August 2011 (b), September 2011 and February 2012 (c), March and August 2012 (d) and September 2012 and March 2013. Arrows indicate the occurrence of wetting and drying cycles in the soil.

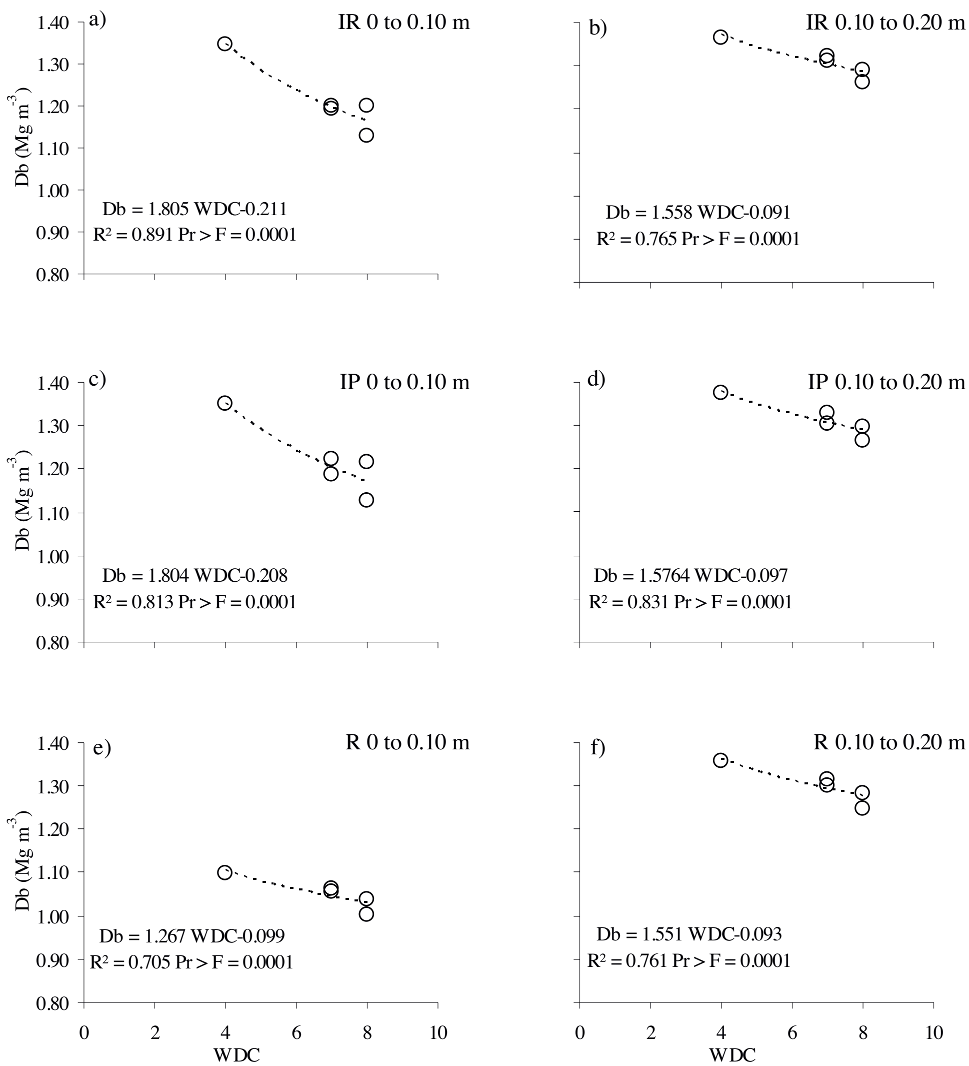

Fig. 4. Soil bulk density (Db) versus the number of wetting and drying cycles (WDC) for IR (a, b), IP (c, d) and R (e, f) in the 0–0.10 m (a, c, e) and the 0.10 to 0.20 m (b, d, f) layer. * Significant ($p < 0.05$).

approximately 0.10 $m^3 m^{-3}$. Therefore, 20 mm of rainfall could increase soil water content to almost the available water capacity if we do not consider losses by evaporation and runoff. Using this criteria, 4, 7, 7, 8 and 8 WDC occurred in the six months preceding each sampling (Fig. 3).

There was a significant negative relationship between Db and the number of WDC ($p < 0.05$) for the three positions and both layers (Fig. 4). It is important to note that the significant relationship is dependent on the initial value of Db. According to da Silva et al. (2014), prior to the first sampling Db was 1.33 $Mg m^{-3}$ in this same area. Therefore, fewer WDC and successive maize crops prior to sampling may cause this high value of Db in 2010. As previously shown, successive maize crops cause the rows and interrows to be in the same place and this may result in inter-row compaction due to cumulative machinery traffic and soil disturbance at the row crop.

Db at the IR position was more strongly influenced by WDC than at the R position as shown by the slope of the Db-WDC relationship. Presumably the IR position was not affected by soil disturbance during sowing or by the plant roots. The IP position showed a slightly lower slope than IR, while the R position exhibited a distinctly different behavior (Fig. 4e) in the 0–0.10 m layer. These results suggest that sampling for soil physical quality under NT should be undertaken by selecting sampling positions within the 0–0.10 m layer. Furthermore, studies relating soil physical properties and plant attributes should have detailed information about the location where the samples were taken.

For the 0.10–0.20 m layer, Db was similar for all sampling positions and the Db by WDC relationship had a smaller slope than for the 0–0.10 m layer. Presumably, this reflected a lower WDC intensity, probably due to less evapotranspiration and soil drying as well as the largest water storage of the rainfall within the 0–0.1 m layer resulting in lower amount of water available to reach 0.10–0.20 m layer depth.

3.3. Water retention curve, available water, air-entry pressure and S index

The van Genuchten equation was fitted to the data for each sampling, position and layer. The parameters were statistically different for each sampling (Table 5) and had coefficients of determination (R^2 approximate = $1 - SQ_{model}/SQ_{error}$) that varied from 0.91 to 0.98, with a significant F value ($p < 0.0001$). This indicated the van Genuchten model provided an excellent fit to the experimental data. The transition from tensiometer to dewpoint potentiameter method did not show discrepancies between

Table 5
The parameters of van Genuchten equation fitted to the WRC data. coefficients of determination (R^2 approximate = 1 − $SQ_{model}/SQ_{residue}$). the air-entry pressure (1/α). S index. field capacity. permanent wilting point and plant available water content for different sampling positions and layers.

Pos.	Samp.	α	*n*	θs	θr	R^2	1/α	S	FC	PWP	PAWC
0–0.10 m											
IR and IP	First	1.122	1.186	0.528	0.215	0.911	0.891	0.037	0.417	0.285	0.132
	Second	0.887	1.200	0.586	0.187	0.948	1.128	0.049	0.444	0.285	0.159
	Third	1.375	1.166	0.560	0.186	0.937	0.727	0.040	0.424	0.287	0.137
	Fourth	1.126	1.228	0.620	0.215	0.971	0.888	0.055	0.446	0.289	0.157
	Fifth	1.079	1.210	0.614	0.203	0.928	0.927	0.053	0.450	0.290	0.160
R	First	1.122	1.325	0.593	0.215	0.911	0.891	0.066	0.386	0.249	0.137
	Second	0.887	1.275	0.615	0.187	0.948	1.128	0.067	0.419	0.247	0.172
	Third	1.375	1.269	0.607	0.186	0.937	0.727	0.065	0.391	0.237	0.154
	Fourth	1.126	1.345	0.649	0.215	0.971	0.888	0.079	0.402	0.248	0.153
	Fifth	1.079	1.302	0.639	0.203	0.928	0.927	0.073	0.414	0.250	0.164
0.10–0.20 m											
IR, IP and R	First	0.296	1.210	0.526	0.250	0.957	3.377	0.035	0.461	0.327	0.134
	Second	0.543	1.165	0.525	0.215	0.957	1.842	0.033	0.445	0.318	0.127
	Third	0.753	1.169	0.521	0.240	0.950	1.329	0.031	0.437	0.326	0.112
	Fourth	0.711	1.195	0.556	0.222	0.979	1.407	0.041	0.447	0.308	0.139
	Fifth	0.827	1.152	0.544	0.220	0.958	1.210	0.033	0.452	0.330	0.123

Pos: position; Samp: sampling; α. *n*. θs and θr: empirical parameter of equation 1; θr: residual soil water content ($m^3 m^{-3}$); θs: saturated soil water content ($m^3 m^{-3}$); FC: field capacity; PWP: permanent wilting point; PAWC: plant available water content ($m^3 m^{-3}$).

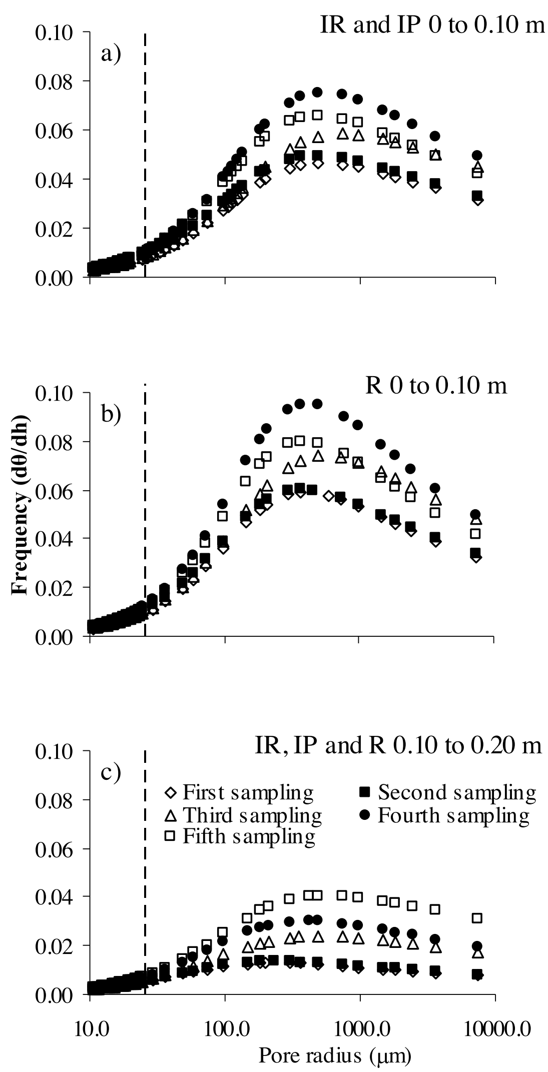

Fig. 5. Derivatives of the soil water retention curves (dθ/dh) versus the pore radius for positions IR and IP (a) and R (b) at the 0–0.10 m and three positions (c) at the 0.10–0.20 m layers, respectively. The dashed line represents the boundary between micro and macropores.

sampling positions, sampling time and depths and did not significantly change the shape of the curves.

A comparison of van Genuchten parameters indicated that α, *n*, θs and θr differed between samplings for both layers, but only *n* and θs were statistically different between positions within the 0–0.10 m layer: both were higher at the R position than at the IR and IP. The different values of *n* and θs indicated that soil water retention and water availability changed in space and time.

The field capacity (FC) and permanent wilting point (PWP) were between 8 and 21% lower at the R position than at IR and IP for all samplings. These differences in the WRC between positions and samplings suggest that studies based on a single sampling or a single position in a NT system can result in different interpretations of the soil physical conditions. In addition, this may explain contradictory results in the literature since the conclusions would be different depending on where and when the soil was sampled. For the 0.10–0.20 m layer R, IP and IR did not show differences in FC and PWP.

PAWC within the 0–0.10 m layer did not show a clear trend between samplings, but values at the R position were approximately 2 to 11% higher, except for the fourth sampling in which PAWC was about 2% higher in IR and IP. Higher PAWC in the fourth sampling in IR and IP positions may again be due to effects of the Brachiaria root system on soil aggregation and water retention. Within the 0.10 to 0.20 m layer, PAWC and the S index showed similar results. In the fourth sampling, PAWC was higher, but it did not show a clear trend among samplings at 0.10 to 0.20 layer. Overall, PAWC values were close to those observed by Tueche and Hauser (2011) in a clay soil, in Cameroon, cultivated with maize and with those generated using pedotransfer functions by Reichert et al. (2009b) for Brazilian clay soils.

Dexter (2004) suggested S = 0.035 as a critical value for soil physical quality, with S > 0.035 indicating good soil quality. Regardless of the sampling position, S > 0.035 at the 0 –0.10 m layer indicated that soil physical quality was not limiting crop growth within this layer. Within the 0.10–0.20 m layer, S > 0.035 was found only in the fourth sampling, which may have been associated with the root system of Brachiaria which was planted between the maize rows. A decrease in soil compaction under Brachiaria within the 0.10–0.20 m layer was reported by Franchini et al. (2010) and attributed to the root system being able to break through layers with higher density. The root system of Brachiaria may cause a biological perforation below the zone of influence of coulters for furrow opening, suggesting the use of

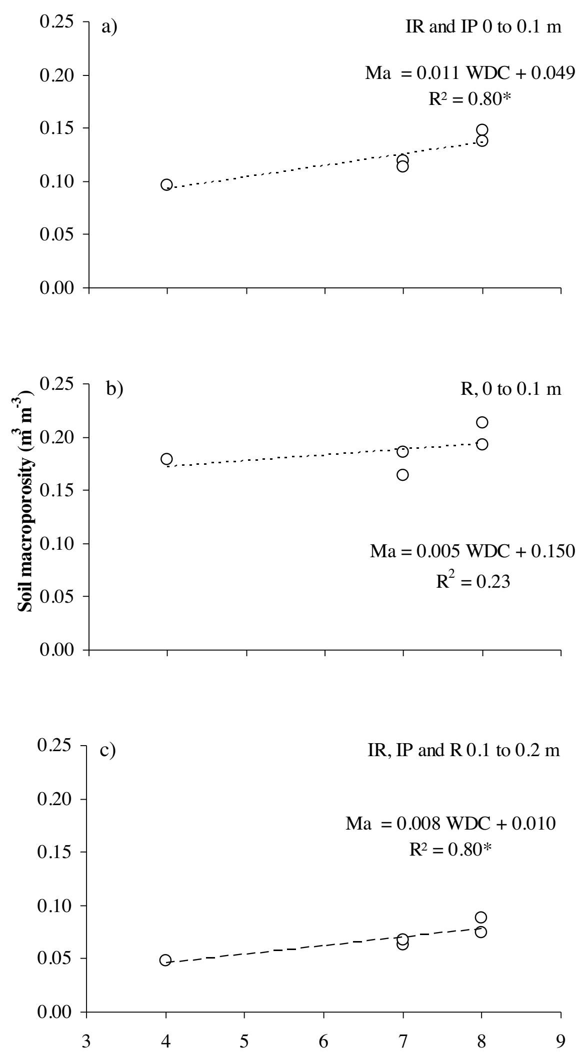

Fig. 6. Soil macroporosity (Ma) versus the number of wetting and drying cycles (WDC) for IR and IP (a) and R (b) in the 0–0.10 m and the 0.10–0.20 m (c) layer. *Significant ($p < 0.05$).

plants with vigorous root growth could replace mechanical loosening practices under NT and thus help improve overall soil quality.

The air-entry pressure varied from 0.73 to 1.13 kPa for the 0 to 0.10 m layer and from 1.21 to 2.76 kPa for the 0.10 to 0.20 m layer. These values were close to those observed by Tormena et al. (1999). An air-entry pressure close to saturation indicates the occurrence of continuous large diameter pores, which promote fast water drainage and soil aeration. Thus, the results show that larger pores existed in the 0–0.10 m layer than in the 0.10 to 0.20 m layer. This result indicates that there may be a “drain barrier” within the 0.10 to 0.20 m layer, which promotes a longer residence time for soil water within the 0.20 m layer, but also imposes higher soil erosion risk.

The air-entry pressure and S index showed wide variability (CV = 8.4–40.0%) between samplings for both layers. This natural variability is a clear indication of temporal fluctuations in soil porosity and pore size distribution. Our results also showed that although Db indicated improvement over time, this is not necessarily reflected by improvements in PAWC or the S index. This suggests that changes occurred mainly in the macropore domain (*i.e.*, large pores). With an increase of macropores, total porosity increases and Db decreases, but S and PAWC are mainly governed by mesopores and upper sized micropores (defined here as pores with diameter $<50\,\mu m$). Pore size distribution was estimated from the WRC through the calculation of equivalent pore diameter. A comparison of van Genuchten parameters indicated that there were no statistical differences between sampling positions within the 0.10–0.20 m layer suggesting that for this layer depth, pore size distribution was independent of sampling positions. There was similarity in shape of the pore size distribution curve for the successive samplings (Fig. 5). Macroporosity, which is represented by pores with a radius $>25\,\mu m$ (on the right side of the line in Fig. 5), increased over time. However, the volume of pores with radius smaller than $25\,\mu m$ did not differ between samplings.

At the R position, higher $d\theta/dh$ values were observed compared to the other sampling positions (Fig. 5). The $d\theta/dh$ ratio showed the greatest difference in pores with a diameter of about $150\,\mu m$, with the R position having values that were between 26 and 35% greater than at IR positions. At pores $<3\,\mu m$, behavior was reversed and IR positions had greatest values. These results agree with findings of Pillai and McGarry (1999) who concluded that intensification of WDC (frequency and intensity) induced by a high rate of evapotranspiration of lab–lab [*Lablab purpureus* (L.) Sweet] and mung bean [*Vigna radiata* (L.) R. Wilezek] improved soil structure. In addition, Yoshida and Adachi (2001) suggested that absorption of water by roots may also contribute to formation of soil structure, because suction and tensile strength promoted by roots is not homogeneously distributed in the soil, possibly inducing microcracks. Thus, the higher $d\theta/dh$ values of the R position cannot be attributed to the sowing operation only, but also to beneficial modifications in the soil structure due to growth and water uptake by crop roots, the latter leading to a higher drying intensity in the soil. According to Bodner et al. (2014), roots can stabilize soil structure against pore degradation, providing changes in soil pore size distribution according to the type of root system. They reported that coarse root systems increased macroporosity while species with dense fine root systems induced heterogenization of the pore space and higher micropore volume.

For the 0.10–0.20 m layer, pore size distribution between samplings was similar for all three sampling positions. This reflects the structural homogeneity within that layer. Pore size distribution within the 0.10–0.20 m layer also exhibited increasing $d\theta/dh$ values with successive samplings. This indicates that WDC can also influence macropores in the 0.10–0.20 m layer, confirmed by the statistically significant correlation between macroporosity (obtained from WRC) and WDC. At the 0.1–0.2 m layer, the slope of macroporosity versus WDC relationship and $d\theta/dh$ values were smaller than IR and IP sampling positions in the 0–0.10 m layer, suggesting the 0.10–0.20 m layer had resilience but it was less dynamic than within the 0–0.10 m layer. There was no significant relationship between macroporosity and the number of WDC ($p < 0.05$) for the R position at 0–0.1 m layer depth (Fig. 6), since samples after soybean had lower macroposity than after maize, possibly due to greater activity of the vigorous root system of maize.

These results are consistent with those obtained by Bodner et al. (2013), indicating that WDC positively influences macroporosity. Similar results were found by Pires et al. (2008) who described the relationship between WDC and pore size distribution showing that the proportion of large-diameter pores and consequently total porosity increased with WDC. Furthermore, Peng et al. (2007) also reported structural changes associated with the WDC resulting in an increased volume of macropores and total porosity (between 2.6 and 16.5%). Arthur et al. (2013) suggested that the wetting process causes expansion of the electrical double layer, differential swelling and air entrapment. Through soil drying, dispersed material settles out of suspension and finer particles settle between coarser particles. Changes due to these two processes are not fully reversible and lead to a progressive development of soil structure.

In general, the predominant pore radius as well as $d\theta/dh$ increased over the samplings (first < second < third < fourth < fifth), except at the fifth sampling within the 0–0.10 m layer. This indicates physical changes related to an increase in macropore proportion over time, suggesting recovery of soil porosity with the WDC. This amelioration of the soil physical quality tends to stabilize, as is shown by the relationship of Db and WDC. However, with the five samplings, this was not observed for the pore size distribution within the 0.10–0.20 m layer.

Within the 0–0.10 m layer, the fifth sampling had smaller $d\theta/dh$ values than in the fourth sampling. This could indicate that a new “equilibrium” was achieved, even with variation that was occurring. This area has been managed under NT since 1980. Therefore, it may have reached physical equilibrium condition, which can be changed or altered by short-term events such as excessive machinery traffic, weather condition variability and changes in crops grown in the crop rotation system. The higher Db and lower pore radius in the first sampling may result from the occurrence of these events negatively impacting the soil structure. Taking into account that the number of WDC in the fourth and fifth samplings was the same, the decrease in soil physical quality may have occurred in association with the soybean crop. The root system of soybeans, grown before the fifth sampling, is less robust than maize or Brachiaria that were grown before the fourth sampling. Additionally, Brachiaria was cultivated between rows of maize. Thus, plants with more vigorous root systems were grown in the same row spacing of soybean and this may have benefited aggregation and soil structure.

Seasonal soil physical changes under NT can be influenced by the crops through variability in row spacing that changes the location of row and interrow positions. Furthermore, it was observed that effects of soil disturbance at sowing, although resulting from localized surface soil loosening, are not persistent until the subsequent crop. This means that residual effects were effective up to five or six months after sowing, but within one year after sowing there was no indication of a residual effect. Our results are consistent with those reported by Alletto and Coquet (2009) who concluded that for surface layers, row and inter-row position was the second most important source of Db variation, but time was the main factor. Evaluations of the pore size distribution enable us to detect relative pore sizes that are mostly affected by these events.

4. Conclusions

In this study changes in soil structure were characterized under NT during five sequential samplings. We found physical variability as caused by sowing, root systems, and wetting and drying cycles. Analysis of sampling position showed that furrow opening causes significant changes to the in-row physical environment, but the effect caused by the soil disturbance was small compared to wetting-drying cycles. Soil bulk density and pore size distribution showed soil physical amelioration throughout the investigation time. The physical properties indicated that the soil under long-term NT may have reached a physical equilibrium condition, which can be modified by short-term events such as excessive machinery traffic, weather conditions variability and changes in crops grown in the crop rotation system. The soil physical properties evaluated suggest that under long-term NT the soil remained physically functional. The results indicated better soil physical conditions due to furrow opening and plant root development at row position in the 0–0.1 m layer compared to interrows sampling positions. Furthermore our results suggest that the 0.1–0.2 m layer may have more importance than the surface layer for physical quality evaluation and monitoring because furrow opening does not alleviate possible soil compaction and roots of most crops may not overcome this compacted layer.

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