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Is Structural Quality as Assessed by the "Profil Cultural" Method Related to Quantitative Indicators of Soil Physical Quality?

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ABSTRACT: Soil and crop management systems change the soil structure, thereby affecting soil quality. The “profil cultural” method (PCM) has been used to identify the effects of management systems on soil structure; however, few studies relate the structures identified by the PCM to quantitative indicators of soil structural quality. This study aimed to quantify soil structures using the PCM and relate these structures to bulk density (Bd), critical bulk density (Bdc), soil aeration capacity (ε_a), least limiting water range (LLWR), and soil air permeability (K_a) under different soil and crop management systems. The study was developed in a long-term experiment (24 years) involving two systems of soil management (no-tillage and conventional tillage) and two systems of crop management (rotation and succession), resulting in four treatments: no-tillage with crop rotation (NTr), no-tillage with crop succession (NTs), conventional tillage with heavy harrowing and crop rotation (CTr) and conventional tillage with heavy harrowing and crop succession (CTs). The PCM was used to identify the different homogeneous morphological units (HMUs) in the soil profile. Undisturbed soil samples were collected for the HMUs that were most represented in the profiles to determine K_a, LLWR, Bd, and ε_a. There was agreement between the HMUs and the quantitative indicators. The LLWR showed greater values for Bdc under no-tillage (NTr = 1.36 Mg m^{-3} and NTs = 1.37 Mg m^{-3}) than under conventional tillage (CTs = 1.31 Mg m^{-3} and CTr = 1.33 mg m^{-3}). The proportion of samples where Bd > Bdc was 23 % under CTs, 77 % under CTr, 32 % under NTs, and 39 % under NTr. The structures that were most restrictive to root development (CΔ, CΔμ, FmtΔμ, and FmtμΔ) show a lower K_a and greater soil penetration resistance as the soil dries. Pores are more continuous and the structure is less restrictive to plant development in no-tillage than in conventional tillage.

Keywords: least limiting water range, air permeability, no-tillage, conventional tillage.

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INTRODUCTION

Sustainable use and conservation of the soil is one of the major scientific and socio-economic challenges in meeting the demand for food, fibre, and energy of future generations. Brazil can contribute significantly to food production due to its potential for expanding agricultural areas and increasing the yield of most crops (Lapola et al., 2014). The no-tillage system (NT) is one of the main soil management systems used in Brazil, but there have been some limitations that are potentially problematic, such as increased soil penetration resistance (Moraes et al., 2014), reduction in aeration (Rodrigues et al., 2011), and soil porosity (Martínez et al., 2008), which may impair sustainable yield in crops.

Soil management systems have an impact on soil structure, resulting in positive or negative changes in chemical, physical, and biological processes (Babujia et al., 2010; Silva et al., 2014a). Different soil physical properties have been used to quantify the effects of soil and crop management systems on soil structure. Bulk density (Bd) is the most widely used because it is simple to determine, despite the difficulty of interpretation due to the influence of texture, mineralogy, and soil organic matter (Håkansson and Lipiec, 2000; Reichert et al., 2009). The least limiting water range (LLWR) was proposed as a multifactor physical indicator of soil quality that integrates the soil physical properties directly related to plant growth, such as soil penetration resistance, soil water potential, and soil aeration, into a single parameter (Silva et al., 1994; Tormena et al., 1998).

Soil compaction and other forms of soil structure degradation modify pore-size distribution and reduce the LLWR and root growth (Guimarães et al., 2013). Soils with a smaller LLWR may exhibit more-frequent physical limitations to crop development, due to spatial and temporal variations in soil water content (Silva et al., 1997; Vieira et al., 2010).

The effects of soil and crop management systems on structure also cover changes in the connectivity and tortuosity of the pores and, consequently, in gas exchanges in the soil. Air permeability (K_a) is a parameter that describes gas flow in the soil (Lipiec and Hatano, 2003) and it is used to quantify the effects of management practices on soil structure (Rodrigues et al., 2011). Studies have found lower macroporosity and K_a in soils under NT (Ball et al., 1994; Rodrigues et al., 2011), but in contrast, water retention increases. However, soil disturbance from sowing equipment can result in more favourable soil physical conditions in the crops root zone (Betioli Junior et al., 2014; Silva et al., 2014b). The K_1 index proposed by Groenevelt et al. (1984), expressed by the ratio of K_a to aeration capacity (ε_a), is also useful in permeability studies. This index makes it possible to investigate whether a difference in K_a can be attributed only to ε_a or to geometric aspects of porosity, such as pore distribution, size, and continuity.

Soil structure has also been studied through visual assessment methods (Newell-Price et al., 2013), such as the *profil cultural* method (PCM), which identifies changes in soil structure caused by management practices through identification of homogeneous morphological units (HMUs) in different layers in the soil profile. Studies have shown that structures identified through the PCM correlate with quantitative soil physical properties such as porosity (Silva et al., 2015), Bd and porosity of aggregates (Neves et al., 2003), and root growth (Cardoso et al., 2006).

There are many reports in the literature that evaluate soil quality under NT and conventional tillage (CT). However, few take into account the influence of spatial variation in the types of structure on soil physical behaviour. The hypothesis of this study is that the HMUs identified by the PCM reflect the soil physical properties quantified by Bd, soil porosity, air permeability (K_a), and least limiting water range (LLWR). The aims of the study were: (1) to identify HMUs by means of the "profil cultural" method, as well as to measure Bd and porosity, K_a, and LLWR in these HMUs under different soil and crop management systems, and (2) to establish relationships among the quantitative and qualitative indicators measured in the different HMUs identified by the PCM.

MATERIALS AND METHODS

Study area

The experimental area is located in the municipality of Londrina in the state of Paraná, southern Brazil, at approximately 23° 11’ S and 51° 11’ W. The soil is classified as a Ferralsol by the FAO system (WRB, 2014) and a *Latossolo Vermelho distroférrico* according to the Brazilian System of Soil Classification (Santos et al., 2013). Soil particle analysis exhibits a composition of 710 g kg^{-1} clay, 80 g kg^{-1} silt, and 210 g kg^{-1} sand, and the soil belongs to the clayey textural class. The climate is subtropical humid (Cfa), with annual rainfall of 1,651 mm and average annual temperature of 21 °C.

Soil and crop management systems

The treatments under evaluation are part of a long-term experiment set up in October 1988. Prior to the experiment, the area had been cultivated with coffee (*Coffea arabica* L.) for 40 years. The experimental design was randomised blocks with four replications in a factorial arrangement. In this study, two soil management systems and two cropping systems were evaluated, resulting in four treatments. For each treatment, two replications (plots) were evaluated, for a total of eight soil profiles. Each experimental plot was 7.5 m in width and 30 m in length.

The following soil and crop management systems were evaluated: no-tillage with crop rotation (NTr), no-tillage with crop succession (NTs), conventional tillage with heavy harrowing and crop rotation (CTr), and conventional tillage with heavy harrowing and crop succession (CTs). Under crop succession, wheat (*Triticum aestivum* L.) was sown annually in the winter and soybean (*Glycine max* L.) in the summer. Crop rotation consisted of a four-year cycle employing the following species in the winter-summer: 1st year, lupin (*Lupinus albus* L.) - maize (*Zea mays* L.); 2nd year, black oats (*Avena strigosa* Schreb.) - soybean; 3rd year, wheat - soybean; and 4th year, wheat - soybean. Conventional tillage consisted of soil tillage with a disk plough (4 reversible discs, 28 inches each) to a depth of 0.20 m, followed by light harrowing to a depth of 0.08 m for the summer crops; and tillage with a heavy harrow (20 discs, 24 inches each) to a depth of 0.15 m, followed by a light harrow to a depth of 0.08 m before sowing the winter crops. Liming was carried out every four years using the same amount of limestone for all treatments, so that the effects are only associated with the soil tillage and crop rotation or succession systems. On average, the application rate of dolomitic limestone was 2 Mg ha^{-1}. Under no-tillage, the limestone was applied to the surface, whereas under conventional tillage, it was incorporated into the soil by harrowing to a depth of 0.15 m.

Assessment of soil structure by the “profil cultural” method

To identify each HMU, a soil sampling pit 1 m wide × 1 m long × 1 m deep was opened in each plot, with two plots for each treatment. The "profil cultural" method described in Tavares Filho et al. (1999) was used to identify structural discontinuities and to identify the soil structures in the profile under evaluation. Soil structure evaluation was carried out in two stages: in the first stage, the arrangement and organisation of the clods in the profile were evaluated using the following categories: C - continuous, F - fissured (cracked), Z - laminar, L - free, and Bw - B horizon showing no signs of alteration due to management. In the second stage, the internal state of the clods was evaluated and described as follows: Δ - compacted, μ - porous, Δμ - low porosity and in process of compaction, and μΔ - porous with evidence of compaction. The presence of roots and size of aggregates were also evaluated. The clods were classified as small (pt), medium (mt), and large (gt). The occurrence of aggregates or very small size is identified as free (L) and the presence of non-aggregated soil as fine earth (TF). After identifying the HMUs, the most representative in the profile were selected, which enabled the collection of at least 24 undisturbed samples in stainless steel cylinders of 5 cm height and 5 cm diameter.

For each HMU, 24 metal cylinders were collected per treatment; for the HMUs that occurred in both plots under evaluation, 12 samples were collected in each plot. For Bw, soil cores were taken from each treatment, for a total of 24 samples, because the B horizon is a genetically developed horizon consisting of a common layer with no obvious anthropogenic change. A total of 288 cores were collected, which were wrapped in aluminium foil to preserve their moisture until the samples were processed. In the laboratory, the samples were placed in a tray with water up to 2/3 of the core height and left for 24 h until complete saturation, which was manifested by the presence of free water at the top of the samples. The samples were then weighed and drained at a water potential of -10 kPa on a tension table similar to that described by Ball and Hunter (1988). Each sample was weighed, and air flow was measured using a constant load permeameter, as described in Figueiredo (2010). Air permeability was calculated according to equation 1:

$$K_a = (Q\eta / A_s)(Z / P) \qquad \text{Eq. 1}$$

in which K_a is soil air permeability (μm^2), Q is the air flow ($m^3 s^{-1}$), η is air viscosity at 20 °C ($N s m^{-2}$), A_s is the area perpendicular to the air movement (m^2), Z is the height of the soil column (m), and P is the pressure difference at the inlet and outlet of the sample (Pa).

After air flow was determined, the samples were divided into 8 groups, each group comprising three samples from each HMU per treatment. The samples were then resaturated and each group of samples equilibrated at matric potentials (Ψ) of -1, -6, and -10 kPa on a tension table, and -30, -50, -100, -300, and -1500 kPa using pressure applied to porous plates, as described in Dane and Hopmans (2002). After achieving water equilibria at each potential, the samples were weighed and soil penetration resistance was determined according to Tormena et al. (1998). The group of samples subjected to the potential of -1500 kPa was removed from the Richards chamber two weeks after the start of the drainage procedure. Their weight was then determined, and soil penetration resistance was measured. The drainage strategy for samples subjected to a potential of -1500 kPa was used to obtain low moisture samples, with the data being used only to determine the penetration resistance curve. The samples were then dried in an oven at ±105 °C for 24 h to determine bulk density (Bd), as per Grossman and Reinsch (2002). After drying, the samples were weighed, and the soil was ground, sieved, and used to determine the permanent wilting point (Ψ = -1500 kPa) with the WP4-T Dewpoint PotentiaMeter (Decagon Devices, 2007). Aeration capacity (εa) was calculated from the difference between the total porosity estimated by Bd and particle density (Flint and Flint, 2002) and the soil water content at a matric potential of -10 kPa.

The water retention curve (WRC) was fitted using the function (Equation 2) described in Ross et al. (1991):

$$\theta = a\psi^b \qquad \text{Eq. 2}$$

This equation was converted to the logarithmic form and bulk density (Bd) was incorporated, to give the equation 3:

$$\ln\theta = \ln(a) + b\ln(\psi) + c\,Bd \qquad \text{Eq. 3}$$

The soil penetration resistance curve (SRC) was estimated by the equation 4, proposed by Busscher (1990):

$$PR = d\theta^e Bd^f \qquad \text{Eq. 4}$$

This equation was converted to the logarithmic form by equation 5:

$$\ln PR = \ln d + e\ln\theta + f\ln Bd \qquad \text{Eq. 5}$$

in which PR is the soil penetration resistance (MPa), θ is the soil water content ($m^3 m^{-3}$), Bd is bulk density ($Mg m^{-3}$), and *a*, *b*, *c, d*, *e*, and *f* are the fitting coefficients.

The LLWR was calculated following the procedures described in Silva et al. (1994). The critical limits used were soil water content at field capacity (Ψ = -10 kPa), soil water potential at wilting point (Ψ = -1500 kPa), and air-filled porosity of 0.10 $m^3 m^{-3}$ as the critical limit for soil aeration. The PR (penetration resistance) considered as limiting was defined based on Moraes et al. (2014), who in the same experiment defined PR = 3.5 MPa for no-tillage and PR = 2.0 MPa for conventional tillage.

Statistical analysis

Data normality for Bd, PR, θ, εa, K_a, and K_1 was verified by the Shapiro-Wilk test. The mean values were compared by the confidence interval ($p<0.05$) as per Payton et al. (2000). Soil water retention and soil penetration resistance curves were fitted through the PROC REG procedure of the SAS 9.0® software (SAS, 2002). The equality of the regression models was tested according to procedures described in Regazzi (1996) to verify: (i) whether the set of equations describing WRC and SRC for the different treatments can be expressed by an equation common to all treatments, (ii) whether the equations show a regression constant common among treatments; or (iii) whether the equations have one or more regression coefficients that are equal.

RESULTS AND DISCUSSION

The HMUs selected in each treatment as well as a description and the depth at which they occur are presented in table 1. Other HMUs, not shown in table 1, were identified, which were not sampled, due to their low representation in the soil profiles evaluated. In general, in the first categorical level of the soil profile, the treatments were characterised by volumes of continuous soil (C), fissured soil (F), and soil unaltered by management practices (Bw). In the second stage, the type C structures displayed an internal state with low visible porosity (Δμ), medium visible porosity (μΔ), or compacted (Δ), characterised as CΔμ, CμΔ, and CΔ. The F structures displayed small (pt) and medium (mt) size clods, and the internal states Δμ and μΔ, designated FptμΔ, FmtΔμ, and FmtμΔ.

The CΔμ and CμΔ HMUs were identified in all the management systems under evaluation, with the representativeness of the structure in the profile being adopted as the criterion, selecting CμΔ in the no-tillage systems (NTs and NTr) and CΔμ in the conventional systems (CTs and CTr) for sampling. The CΔ structure was identified in NTr and CTs in one of the replications of each treatment, but it was only sampled in NTr. The structures FmtΔμ and FmtμΔ were also identified in all the management systems evaluated. Following the

Table 1. Description of the homogeneous morphological units (HMU) and the depth of occurrence of the HMU in a Ferralsol under conventional tillage (CT) and no-tillage (NT), and crop management consisting of rotation (r) and succession (s)

HMU	Description	CTr	CTs	NTr	NTs
		Depth			
		m			
CΔ	Volume of continuous soil, absence of visible pores, compacted	-	-	0.00-0.18	-
CΔμ	Volume of continuous soil with little porosity, in process of compaction.	0.00-0.35	-	-	0.00-0.30
CμΔ	Volume of continuous soil, porous internal structure showing signs of compaction.	-	-	0.07-0.30	0.15-0.30
FmtμΔ	Volume of fissured (cracked) soil, medium clods, porous internal structure showing signs of compaction.	-	-	0.05-0.13	0.05-0.10
FmtΔμ	Volume of fissured (cracked) soil, medium clods with little internal porosity, in process of compaction.	0.05-0.25	0.10-0.25	-	-
FptμΔ	Volume of fissured (cracked) soil, small clods with porous internal structure showing signs of compaction.	0.00-0.05	0.00-0.05	-	-
Bw	Volume of soil showing no signs of alteration due to management, latossolic B horizon.	0.35-1.00	0.30-1.00	0.30-1.00	0.30-1.00

- : not determined.

criterion of greater representativeness, FmtΔμ was sampled in CTs and CTr, and FmtμΔ in NTr and NTs. The FptμΔ structure was most represented in CTr, its occurrence not being seen under the no-tillage systems.

The volumes of C soil are characterised by a lower volume of roots and lower biological activity in relation to the volumes of F soil (Fregonezi et al., 2001; Silva et al., 2014a; Silva et al., 2015). The internal state Δ comes from degradation of the structure by heavy machinery and indicates a compacted structure that strongly restricts root development (Neves et al., 2003; Ralisch et al., 2010) and is characterized by the absence of visible porosity. The internal states Δμ and μΔ are intermediate with respect to Δ (compacted) and μ (noncompacted). The Δμ indicates a compact structure, but shows few visible pores; μΔ shows signs of anthropogenic action, but with visible pores (Silva et al., 2015).

The data set for K_a and K_1 did not meet the assumptions of normality and were log transformed (Ball and Hunter, 1988), with the form (log K_a+1) being used for K_a, as per Betioli Junior et al. (2014). The average values of soil air permeability (K_a), pore continuity index (K_1), aeration capacity (ε_a), and bulk density (Bd) are presented in table 2. The effects of the management system on soil structure, visually identified by the PCM, were confirmed by the wide variation in the mean values of soil physical properties and indicators under evaluation (K_a, K_1, ε_a, and Bd) for the different HMUs.

Values for K_a were related to the HMUs determined by the changes in soil structure caused by tillage and crop management. A greater value for K_a was found in Bw ($p<0.05$) under the CTr, NTr, and NTs systems whereas, under CTs, the value for K_a seen in Bw did not differ from FptμΔ ($p<0.05$). In the clayey Ferralsols, Bw (with no visible alterations due to management) coincides with the latossolic B horizon and exhibits high structural porosity, formed by the stacking of microaggregates, resulting in a greater value for K_a. In the absence of anthropogenic alteration, clayey Ferralsols display no physical limitations, due to a structure characterised by the predominance of highly stable micro-aggregates (Neves et al., 2003; Volland-Tuduri et al., 2005). A description by the “profil cultural” method of a clayey Ferralsol with no anthropogenic action, made by Neves et al. (2003), demonstrates that varied structures occur naturally, such as L (free), micro-aggregate continuous (Cμ corresponding to the Bw horizon), and fissured (Fμ) soils. However, high porosity and the absence of signs that would indicate compaction or physical restraint of any type are common to all of them. Under the CTs management system, FptμΔ exhibits fissures and visible porosity, which possibly contributed to an air flow similar to that of the Bw.

Under the NTr management system, in the structure classified as CΔ, the values for K_a and K_1 were lower ($p<0.05$) than in FmtμΔ, although both structures displayed similar values for Bd and εa ($p>0.05$) (Table 2). Compared to CΔ, the results for K_a and K_1 show that the FmtμΔ structure has better pore distribution, size, and continuity, possibly associated with the presence of fissures. The F structures are formed by a group of clods with a network of fissures between them, which results in pores of sufficient size to ensure root development and water and gas flow, even with a high value for Bd (Neves et al., 2003). In the CΔ structure, limitations on air flow are explained by the continuous mode of organisation, the absence of visible pores, and soil compaction from management practices.

Soil air permeability (K_a) showed a positive correlation with ε_a and a negative correlation with Bd (Table 3). All the correlations were significant under conventional tillage, and the HMUs with similar values for K_a also showed similar values for K_1 (Table 2). However, this behaviour did not occur under the no-tillage system, irrespective of crop rotation or succession. Most of the HMUs under no-tillage showed a moderate to weak correlation ($r<0.70$) with Bd and ε_a (Table 3), and 37 % of the correlations were not significant. Under the no-tillage system, the FmtμΔ HMUs with crop rotation and CμΔ and CΔμ with crop succession showed values for K_1 similar to Bw ($p<0.05$), but lower values for K_a than Bw (Table 2). This suggests a greater heterogeneity and complexity of the porous

Table 2. Mean values for air permeability (K_a), pore continuity index (K_1), aeration capacity (εa), and bulk density (Bd) in different homogeneous morphological units (HMU) in a Ferralsol under conventional tillage (CT) and no-tillage (NT) with crop rotation (r) and succession (s)

HMU	$\log_{10} K_a$+1	$\log_{10} K_1$	ε_a	Bd
	μm²		$cm^3 cm^{-3}$	$Mg m^{-3}$
		CTr		
FptμΔ	1.02 a	0.92 a	0.10 b	1.31 b
FmtΔμ	0.76 a	0.85 a	0.08 a	1.37 c
CΔμ	0.98 a	1.03 a	0.08 a	1.38 c
Bw	1.57 b	1.43 b	0.14 b	1.18 a
		CTs		
FptμΔ	1.45 b	1.27 b	0.16 b	1.26 b
FmtΔμ	0.75 a	0.88 a	0.09 a	1.29 b
Bw	1.47 b	1.36 b	0.13 b	1.19 a
		NTr		
FmtμΔ	1.01 b	1.14 b	0.08 ab	1.38 c
CΔ	0.66 a	0.75 a	0.08 a	1.35 bc
CμΔ	0.87 b	0.90 a	0.10 bc	1.33 b
Bw	1.40 c	1.35 b	0.11 c	1.24 a
		NTs		
FmtμΔ	0.78 a	0.93 a	0.09 a	1.36 c
CΔμ	1.09 a	1.16 ab	0.09 ab	1.35 bc
CμΔ	1.11 a	1.14 ab	0.09 ab	1.32 b
Bw	1.59 b	1.49 b	0.13 b	1.20 a

Mean values followed by the same letter in a column do not differ by confidence interval at 5 % probability.

Table 3. Pearson correlation between air permeability ($\log_{10} K_a$+1) and bulk density and aeration porosity in the homogeneous morphological units (HMU) identified under different management systems

Management systems	Homogeneous morphological units			
CTr				
	FptμΔ	FmtΔμ	CΔμ	Bw
$\log_{10}$ εa(1)	0.84^*	0.76^*	0.43^*	0.92^*
Bd(2)	-0.83^*	-0.63^*	-0.68^*	-0.91^*
CTs				
	FptμΔ	FmtΔμ	Bw	
$\log_{10}$ εa	0.82^*	0.60^*	0.93^*	
Bd	-0.78^*	-0.43^*	-0.94^*	
NTr				
	FmtμΔ	CΔ	CμΔ	Bw
$\log_{10}$ εa	0.44^*	$0.32^{n.s.}$	0.50^*	0.85^*
Bd	-0.66^*	$-0.29^{n.s.}$	$-0.22^{n.s.}$	$-0.44^{n.s.}$
NTs				
	FmtμΔ	CΔμ	CμΔ	Bw
$\log_{10}$ εa	0.47^*	0.66^*	0.54^*	0.93^*
Bd	$-0.38^{n.s.}$	-0.64^*	-0.52^*	$-0.15^{n.s.}$

(1) $\log^{10}$ εa: logarithm of the aeration capacity. (2) Bd: bulk density. *: significant at 5 % probability; n.s.:no significant. CTr = conventional tillage with crop rotation; CTs = conventional tillage with crop succession; NTr = no-tillage with crop rotation; NTs = no-tillage with crop succession.

system under no-tillage, in addition to the presence of a network of narrower and more tortuous pores that reduce soil aeration. As discussed by Cavalieri et al. (2009), under a long-term no-tillage system, pore connectivity is more determinant of the dynamic processes related to the flow of water and gas than macroporosity, total porosity, and bulk density, and establishes the physical functionality of the soil.

In general, log K_a+1 had a high coefficient of variation (26 to 71 %), explaining the absence of statistical differences between types of structures with subtle differences, such as CΔμ and CμΔ. However, K_a was sensitive to identify differences in structures with contrasting properties, such as Bw and CΔ. In the field, the size of the aggregates may vary and make it difficult to distinguish intermediate structures in the second categorical level of the method, such as Δμ and μΔ (Neves et al., 2003).

The coefficients of the water retention curve (WRC) and soil resistance curve (SRC) models are presented in table 4. The tillage system, cropping system, and the HMU did not influence the WRC, so the WRC was expressed by one equation for all treatments. The SRC was significantly influenced by tillage and crop management systems (Table 4). The different HMUs had no significant influence on WRC or SRC, probably because Bd incorporated the effect of the HMU. The results obtained by Fregonezi et al. (2001), Neves et al. (2003), and Domingos et al. (2009) indicate that the levels of compaction described by the HMUs were captured by Bd. The positive coefficient for Bd in the WRC indicates that soil water retention is positively related to Bd (Table 4), as previously identified in tropical Oxisols (Tormena et al., 1998).

The SRC was positively influenced by Bd and negatively influenced by θ (Table 4). The higher coefficients relative to θ in the SRC for the no-tillage system (NTr and NTs) indicate that for similar values of Bd and θ, PR is higher under no-tillage. Studies indicate higher values for PR under NT (Tavares Filho et al., 2001; Martínez et al., 2008; Guan et al., 2015), which may be associated with denser aggregates and narrow pore size distribution resulting from machine traffic and minimum soil disturbance (Franchini et al., 2007; Barreto et al., 2009).

The PR estimated by the equations shown in table 4, using the densities obtained in each HMU and the water content obtained at the matric potentials of -0.01, -0.08, -0.30, and -1.00 MPa, are given in figure 1. Irrespective of the tillage system, at field capacity (-0.01 MPa), PR is not restrictive to root growth, but as the soil dries, the increase in PR is more pronounced in HMUs that showed the degrading effects of the management system on soil structure and that had higher values for Bd (Figure 1). For layers below 0.40 m, where the Bw horizon occurs, no effects from the management system on the soil structure were seen, explaining the difference in behaviour of the PR curves between Bw and the other HMUs.

Figure 2 shows the LLWR and corresponding critical bulk densities (Bdc) taken as the Bd value at which the LLWR is equal to zero. For Bd > Bdc, we suggest that the soil physical condition presents strong physical limitations to plant development due to aeration and penetration resistance. The behaviour of the PR curves (Figure 1) and the values where Bd > Bdc (Figure 2) show that the HMUs identified as more restrictive (CΔ, CΔμ, FmtΔμ, and FmtμΔ) can severely limit root growth in plants at matric potentials below field capacity. In contrast, HMUs characterised by high visible porosity (CμΔ and Bw) indicated conditions favourable to root development. The results showed that the visible effects

Table 4. Equations for soil water retention curve and penetration resistance curve of a Ferralsol under no-tillage (NT) and conventional tillage (CT) with crop rotation (r) and succession (s)

Treatment	Function
Soil water retention curve (F = 1,307; p<0.001; R² = 0.90)	
NTs, NTr, CTs, and CTr	$\theta = e^{(-0.065 + 0.134 \times Bd)} \times \Psi^{-0.068}$
Soil penetration resistance curve (F = 167; p<0.0001; R² = 0.83)	
NTs	$PR = 0.012\ \theta^{-4.147} \times Bd^{6.812}$
NTr	$PR = 0.012\ \theta^{-4.244} \times Bd^{6.812}$
CTs	$PR = 0.012\ \theta^{-3.803} \times Bd^{6.812}$
CTr	$PR = 0.012\ \theta^{-4.042} \times Bd^{6.812}$

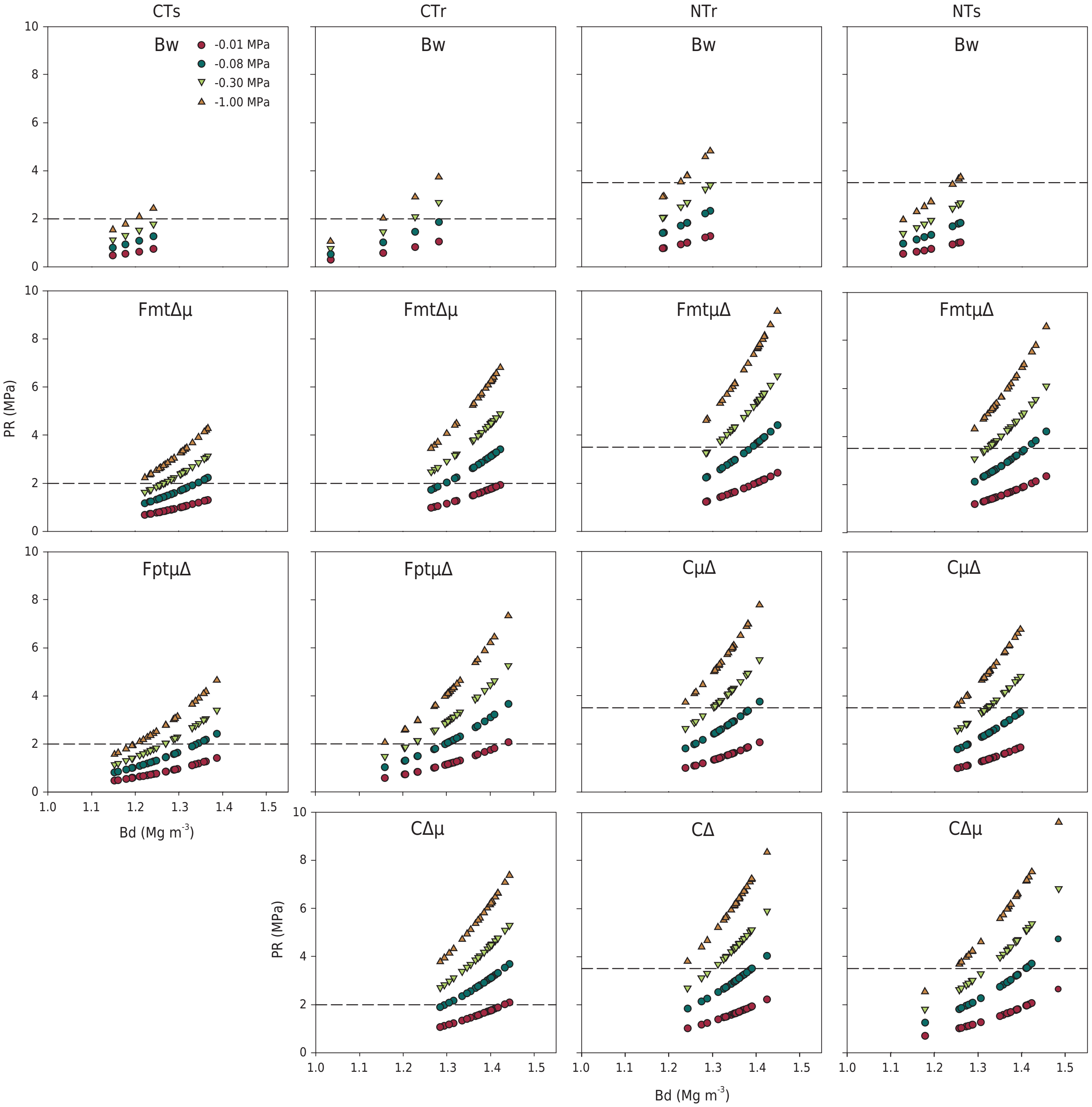

Figure 1. Soil penetration resistance (PR) as a function of soil bulk density (Bd) of the morphological units at four matric potentials in a Ferralsol under conventional tillage (CT) and no-tillage (NT) with crop rotation (r) and succession (s). The dashed line indicates the critical limit for penetration resistance of 2 MPa for conventional tillage and 3.5 MPa for no-tillage.

from the management system on soil structures, such as the reduction in visible porosity and the presence of compaction, increase the PR as the soil dries or promote reduction in soil matric potential (Figure 1). Although the HMU, FmtΔμ, and FmtμΔ display high PR, the presence of fissures and biopores formed by soil fauna and root decomposition can reduce the effect of compaction on root development, since roots tend to grow mainly in pores and fissures (White and Kirkegaard, 2010). The results obtained by Tavares Filho et al. (2001), Cardoso et al. (2006), and Silva et al. (2015) demonstrated less root volume in the continuous C structures than in structures with fissures (F). According to Cardoso et al. (2006), for a PR of 3 MPa, the soybean crop exhibited a root volume three times smaller in the continuous structures than in the fissured structures. For example, under NTr, PR behaviour between CΔ and FmtµΔ is similar. However, the values for K_a indicate a reduced air flow in CΔ, suggesting that in this structure the roots find conditions that are more restrictive to growth, such as a smaller number of macropores and/or fissures and a greater susceptibility to oxygen deficit in the root zone.

The LLWR for the soil and crop management treatments is shown in figure 3. The PR and aeration were limiting in all treatments (Figure 3) since over most of the LLWR, the soil water content at limiting penetration resistance was greater than the permanent wilting point, while the soil water conten at air-filled porosity of 0.10 m^3 m^{-3} was smaller than water content at field capacity. The proportion of samples where Bd > Bdc was 23 % under CTs, 77 % under CTr, 32 % under NTs, and 39 % under NTr. The greater proportion of samples with restrictive Bd values indicates the greater structural and soil physical degradation under CTr.

Critical bulk density (Bdc) was very similar between CTs (1.31 Mg m^{-3}) and CTr (1.33 Mg m^{-3}), and between NTr (1.36 Mg m^{-3}) and NTs (1.37 Mg m^{-3}), but always greater under the no-tillage system, demonstrating that the no-tillage system provides a more efficient structure for the diffusion and transport of gases and fluids under conditions of higher density. Higher values for Bdc under the no-tillage system are a result of the higher critical limit adopted under NT (Moraes et al., 2014). It is important to consider that under no-tillage systems the process of soil structure development is different from under conventional tillage, which also explains the difference in criteria for PR. For example,

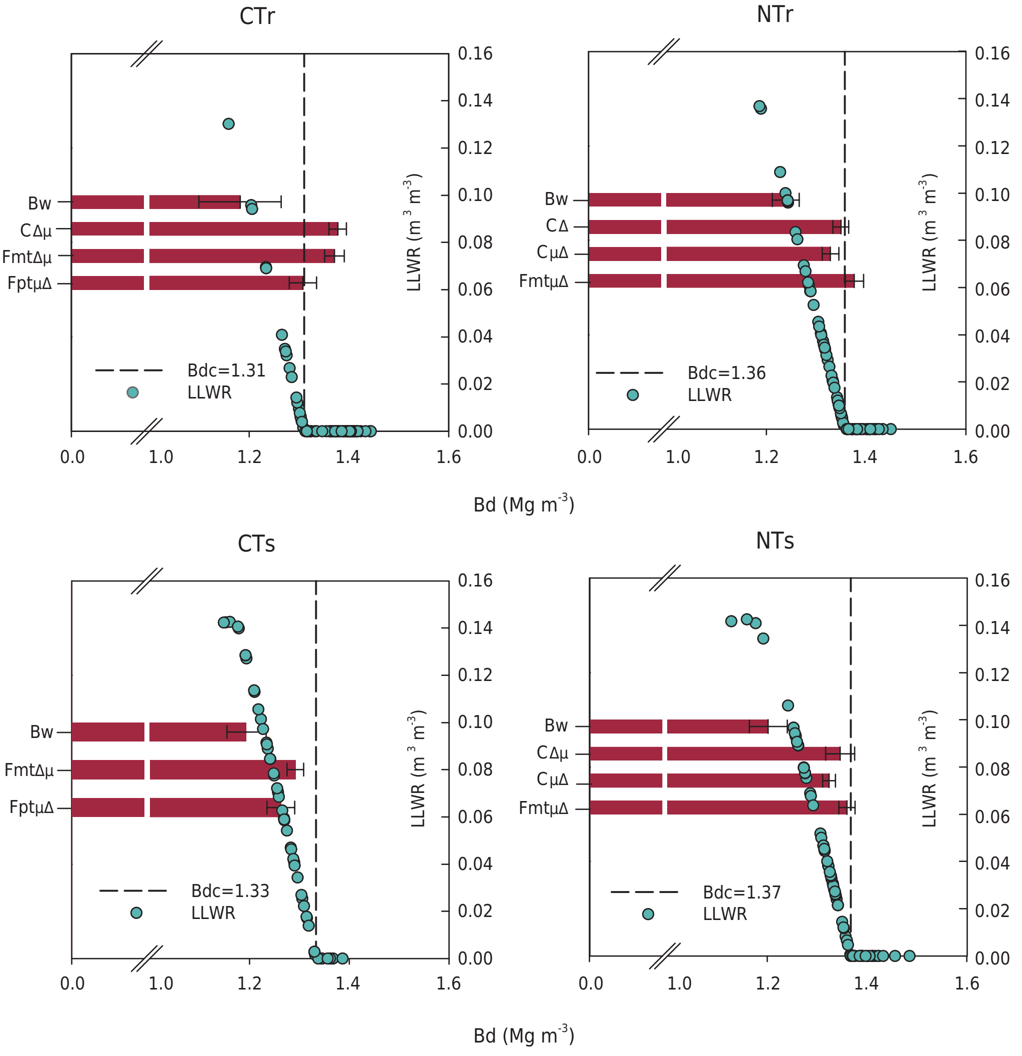

Figure 2. Bulk density (Bd) of the homogeneous morphological units and variation in the least limiting water range (LLWR) as a function of Bd.

the roots of previous crops left a network of pores that remain available to succeeding crops, since there is no turning or inversion of the layers, which favours root development under conditions where penetration resistance and bulk density are higher (Williams and Weil, 2004). In soils under no-tillage, there is improvement in pore connectivity, which explains the need for a greater volume of macropores under soils tilled annually than under NT (Reichert et al., 2009). In the same study area, Franchini et al. (2012) found that losses in soybean yield occur when the water requirement satisfaction index for the crop is less than 0.80 under conventional tillage and 0.70 under no-tillage, showing that the soil structure under no-tillage reduces the effects of water stress.

The "profil cultural" method was efficient in discriminating and qualifying zones with different structural conditions under the management systems evaluated. The quantitative physical indicators (K_a, PR, and LLWR) confirmed the morphological differences identified by the "profil cultural" method. The relationship between the qualitative and quantitative soil structure measurements were consistent; thus, the structures characterised as restrictive to root development displayed greater limitation as measured by the quantitative indicators. The results showed that K_a was more sensitive in detecting differences between the HMUs than were Bd, PR, and LLWR, which can be explained by visible porosity being one of the criteria used in the soil profile. The K_a is considered an indicator sensitive in detecting changes in pore distribution (Silva et al., 2009; Betioli Junior et al., 2012), whereas PR is not able to pick up differences on a smaller scale, such as visible pores or the presence of fissures (Tavares Filho et al., 2001; Cardoso et al., 2006).

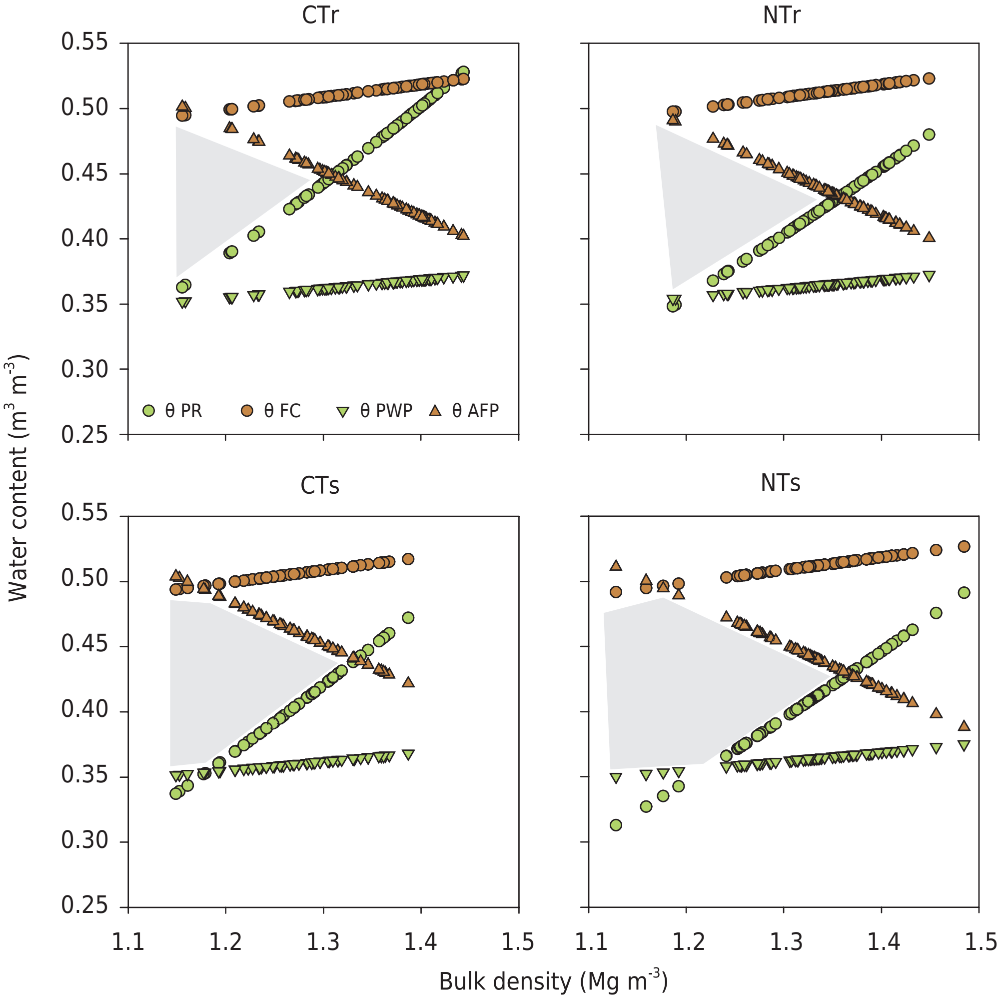

Figure 3. Variation in soil volumetric moisture at field capacity (θFC), permanent wilting point (θPWP), aeration porosity at 0.10 $m^3 m^{-3}$ (θAP), and penetration resistance (θPR) as a function of density for a Ferralsol under conventional tillage (CT) and no-tillage (NT) with crop rotation (r) and succession (s). The grey area represents the least limiting water range (LLWR).

CONCLUSIONS

The structural differences identified by the “profil cultural” method were reflected in the measurements of air permeability (K_a), pore continuity index (K_1), soil bulk density, soil penetration resistance, and least limiting water range (LLWR). Sampling based on the spatial variability of the soil structure allowed characterisation of the structures that showed great variability in the behaviour of soil physical properties. The consistent relationship between the qualitative and quantitative results confirms the ability of the “profil cultural” method in identifying spatial variability in the structure, and the potential of the soil to exert its agronomic potential relative to physical quality.

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