CHARACTERIZATION OF SOIL STRUCTURE AND POROSITY UNDER LONG-TERM CONVENTIONAL TILLAGE AND NO-TILLAGE SYSTEMS(1)

João Tavares Filho(2) & Daniel Tessier(3)

ABSTRACT

Different management systems tend to modify soil structure and porosity over the years. The aim of this study was to study modifications in the morphostructure and porosity of dystroferric Red Latosol (Oxisol) under conventional tillage and no-tillage over a 31- year period. The study began with the description of soil profiles based on the cropping profile method, to identify the most compact structures, define sample collection points for physical and chemical analysis, and determine the water retention curve. A forest soil profile was described and used as reference. The results showed that, under conventional tillage, the microaggregate structure of the Oxisol was fragmented between 0 and 0.20 m, and compact (bulk density = 1.52 Mg m^{-3}) in the sub-surface layer between 0.20 and 0.50 m. Under no-tillage, the structure became compacted (bulk density = 1.40 Mg m^{-3}) between 0 and 0.60 m, but contained fissures and biopores. The volume of the class with a pore diameter of ≥ 100 µm under no-tillage was limited, but practically non-existent in the conventional management system. On the other hand, the classes with a pore diameter of < 100 µm were not affected by the type of soil management system.

Index terms: Latosol/Oxisol, soil management, cropping profile method, water retention curve.

---

(1) Recebido para publicação em setembro de 2008 e aprovado em julho de 2009.

(2) Professor da Universidade Estadual de Londrina – UEL. Campus Universitário, CCA/Agronomia, Caixa Postal 6001, CEP 86051-990 Londrina (PR). E-mail: tavares@uel.br

(3) Pesquisador do INRA – Institut Nacional de Recherche Agronomique. Centre de Recherche de Versailles – Grignon (Science du Soil). RD10. 78026 – Versailles Cedex. E-mail: tessier@versailles.inra.fr

RESUMO: *CARACTERIZAÇÃO DA ESTRUTURA E DA POROSIDADE DE SOLO SOB PREPARO CONVENCIONAL E SEMEADURA DIRETA DE LONGA DURAÇÃO*

Os diferentes manejos do solo tendem a modificar a sua estrutura e porosidade ao longo dos anos de manejo. Dessa forma, este trabalho teve por objetivo estudar as alterações morfoestruturais e da porosidade de Latossolo Vermelho distroférrico sob preparo convencional e semeadura direta por 31 anos. O estudo baseou-se inicialmente na descrição dos perfis de solo, a partir do método do perfil cultural, para qualificar as estruturas mais compactas e definir os locais de coleta de amostras para as análises físicas e químicas e obtenção da curva de retenção de água. Um perfil de solo sob mata foi descrito e usado como referência. Os resultados permitiram concluir que, no preparo convencional, a estrutura microagregada do Latossolo Vermelho tornou-se fragmentada entre 0 e 0,20 m e compacta (densidade do solo de 1,52 Mg m^{-3}*) em subsuperfície, entre 0,20 e 0,50 m. Na semeadura direta, a estrutura tornou-se também compactada (densidade do solo de 1,40 Mg m*$^{-3}$*) entre 0 e 0,60 m, porém, com a presença de fissuras e bioporos e a classe de poros com diâmetro ≥ 100 μm, apresentou volume limitado, tendo desaparecido no preparo convencional, enquanto as classes de poros com diâmetro < 100 μm não foram alterados pelo tempo de manejo do solo.*

Termos de indexação: Latossolo, manejo de solo, perfil cultural, curva de retenção de água.

INTRODUCTION

Soil is an integral part of most terrestrial ecosystems, and its role in food production is essential. However, in recent years, soil degradation has become a major environmental problem in most countries (Lesturgez, 2005; Nicolodi et al., 2007).

The Oxisols, commonly found in the State of Paraná, is one of the richest and most productive soils in Brazil (Vieira, 1989; Tavares Filho & Tessier, 1998). Following the incorporation of Oxisols into productive agricultural systems, structural alterations and soil compaction have been observed (Tavares Filho et al., 1999; Klein & Libardi, 2000; Tavares Filho et al., 2001; Giarola et al., 2007). The soil physical characteristics are interdependent and an alteration in any of them normally leads to changes in the soil system as a whole (Vieira, 1989). Accordingly, structural alterations may lead to significant changes in water infiltration and plant availability, as well as in root aeration, and may reduce soil exploration by the roots of cultivated plants, with major consequences in terms of soil degradation and reduced crop yields.

Of the soil management components, tilling has perhaps the greatest influence on the soil physical behavior, since it influences the structure directly, with or without mobilization (Vieira, 1989). Conventional soil preparation causes structural changes that affect soil porosity, density, water retention and storage, as well as aggregate stability. It also influences biological groups that participate in physical and chemical processes. It is believed that soil conservation methods such as no-tillage (direct seeding) can help minimize erosion and improve soil quality, increasing fertility, organic matter, surface cation exchange capacity and humidity (Tavares Filho et al., 2001; Nicolodi et al., 2007; Benito et al., 2008), besides causing less structural changes in the soil.

Soil use intensity is another important factor which, when combined with inappropriate humidity conditions, contributes to alter the soil structural quality. This can lead to the appearance of large quantities of compacted soil with increased penetration resistance, due to increased density and lower macroporosity (Ivo & Mielniczuk, 1999; Tavares Filho et al., 2001; Collares et al., 2006).

Although these problems have existed ever since the beginnings of agriculture, their current extension and impact are considered to be extreme (Lal & Stewart, 1990). Qualitative diagnoses of different soil management systems associated with laboratory analyses may be useful when choosing the most appropriate management to maintain or increase yields. Accordingly, the aim of this study was to study modifications in the morphostructure and porosity of a dystroferric Red Latosol (Oxisol) under conventional tillage and direct seeding over a period of more than thirty years.

MATERIALS AND METHODS

The study was carried out in Western Paraná State (24 ° 48 ” S; 53 ° 18 ” W; average altitude 682 m asl; Cfb climate according to the Köppen classification), on an Oxisol with a slope ranging from 3.4 to 5.2 %. The data were collected in July 2007 from areas under two soil management systems in two agricultural areas: a no-tillage (NT) system and a conventional tillage (CT) system, both since 31 years. An area of native forest (F) was used as reference. Crop rotation in the NT and CT systems followed this sequence: soybean/corn in the summer and wheat in the winter.

To begin with, the soil profiles were described by the cropping profile method (Tavares Filho et al., 1999; Roger-Estrade et al., 2004; Lagacherie et al., 2006) to characterize the type and spatial organization of compact soil structures (morphologically homogeneous units, or MHUs, according to Neves et al. (2003)). The analysis was performed in three trenches (1.0 x 1.0 x 1.5 m) in each of the three areas (F, NT and PD), at a randomly selected location, with a distance of 100 m between the trenches, which were arranged along the slope (one in the highest part, with least inclination; a second in the middle of the area, with average inclination; and a third in the lowest area, with greatest inclination). The soil profiles were described after the wheat had been harvested and before soybean was planted. After characterizing the soil profiles, two persons analyzed the possible differences between the descriptions independently, to draw conclusions on how soil samples ought to be collected for laboratory analysis. Thereafter, it was concluded that there was a very similar distribution of structures among the profiles in all three described areas, which can be explained by the fact that the soil management methods in the areas were similar. Accordingly, one of the three trenches was chosen – the central one –to collect five deformed soil samples from each of the three areas, totaling 15 for the three areas (F, NT and PD). In the case of NT and CT, the compact MHUs (MHU_{Δ}), with greatest soil density were sampled, to determine contents of clay, soil bulk density (Bd), organic matter (OM), water pH and cation exchange capacity following Embrapa (1997).

To classify the porosity distribution for each area, pore diameters were obtained from the soil water retention curve, based on the relationship between the water potential value in the sample and the value of the equivalent pore diameter (the maximum value of a water-saturated cylindrical pore). To obtain this curve, after the description of the MHU, as reported above, five columns of non-deformed soil were collected, totaling 15 samples for the three areas (F, NT and PD – in the case of NT and CT, the compact MHUs (MHU_{Δ}), with greatest soil density). The columns (volume 15–20 cm^3) were stored in plastic bags and these within polystyrene boxes, to preserve the humidity content. In the laboratory, the simultaneous evolution in water content and apparent volume of these columns was studied at different water potentials (Ψ), using the following techniques:

- Filtration apparatus (Tessier & Berrier, 1979; Tavares Filho et al., 2005), where the matrix potential (Ψ) is fixed by submitting the soil columns to a pneumatic pressure of 1 kPa to 100 kPa for one week, to study the pores with a diameter between 300 and 3 μm;
- Richards cells (Richards, 1947), whereby the matrix potential (Ψ) is fixed by submitting the soil columns to a pressure of 320 to 1,600 kPa, to study the pores with a diameter between 9.4 and 0.188 μm;
- Saturated saline solutions (Tavares Filho, 1995; Matieu & Pieltan, 2001), where the soil columns are placed inside a desiccator in which the relative humidity is fixed by means of saline solutions to potentials between -2,800 and -107,000 kPa; the equilibrium was reached when the evolution curve of soil column weight reached a constant level, to study the pores with a diameter between 0.104 and 0.0028 μm;
- Greenhouse drying at 105 °C, at a pressure of 1E + 06 kPa, for pores of diameter as small as 0.0003 μm.

The results were expressed as solid phase volume, following Kilasara & Tessier (1991) and Tavares Filho et al. (2005). This reference is most appropriate for materials with different solid phase mass, making a comparison possible. The void volume was expressed as void ratio (e), calculated by dividing the void volume by the solid volume. For water volume, the water ratio (w) was used, given by the water volume divided by solid volume. The higher the void ratio, the more porous and therefore less dense is the soil. Calculations were based on the following measurements:

- For each water potential, the apparent volume of soil columns was determined by the kerosene method, with the wet (Mw) and dry (Md) masses and the thrust exercised by the sample in kerosene (Mk). The volumetric mass of kerosene is $\delta = 0.782$ g cm^{-3} (Mathieu & Pieltain, 1998);
- Particulate density, determined by the pycnometer method (Mathieu & Pieltain, 1998), was 2.96 Mg m^{-3}.

The mean values for the water retention curve were presented for nine replications, together with the standard deviations for each matrix potential considered. In addition, to characterize the heterogeneous soil structure accurately, the coefficient of variation and a 95 % confidence interval were calculated for each case.

RESULTS AND DISCUSSION

The microaggregate structure of the soil under native forest, in the whole profile analyzed (0–1 m) (Table 1), was morphologically homogeneous (MHU_{μ}) with weak cohesion of aggregates and columns when dry, containing pores within and between aggregates, and biopores. The texture in this profile was characterized by the predominance of clay fraction (799 g kg^{-1}). The soil density (Sd = 1.04 Mg m^{-3}) corresponded to that of a non-compact microaggregate structure. In terms of other properties, an organic

Table 1. Description of morphologically homogeneous units (MHU)(1), according to the cropping profile(2), and physical-chemical properties (clay content (Arg.), soil bulk density (Sd), organic matter (OM), pH and cation exchange capacity (CEC)) for each MHU, observed in soil under two management systems and under forest, and crop yield for soybean and corn in the two areas under study

Soil under native forest - reference	Agricultural system	
	No-Tillage (NT)	Conventional tillage (CT)
	Descrition of MHUs	
UMH_{μ}	$MHU_{F\Delta}$	$MHU_{C\Delta}$
Morphological unit present between 0 and 1 m of depth, not influenced by man, micro aggregate and with biopores present.	Morphological unit present between 0 and 0.6 m of depth, influenced by man, compact and with biopores present. As of 0.6 m, the soil presents a MHU similar to that of soil under forest.	Morphological unit present between 0 and 0.2 m of depth, influenced by man, disaggregated soil with compact columns. From 0.2 to 0.5 m of depth, the compaction becomes more pronounced (laminar structure), with no biopores. As of 0.5 m, the soil presents a MHU similar to that of soil under forest.
	Physical - chemical characteristics of umhs described	
Clay: 799 g kg^{-1} Sd: 1.04 Mg m^{-3} OM: 23.6 g dm^{-3} pH_{H_2O}: 4.7 CEC: 6.7 $cmol_c$ dm^{-3}	Clay: 789–800 g kg^{-1} Sd: 1.40–1.08 Mg m^{-3} OM: 20.3–18.6 g dm^{-3} pH_{H_2O}: 5.6–4.5 CEC: 5.5–6,0 $cmol_c$ dm^{-3}	Clay: 778–800 g kg^{-1} Sd: 1.21–1.52 Mg m^{-3} OM: 8.6–7.8 g dm^{-3} pH_{H_2O}: 5.2–4.5 CEC: 4.8–4.9 $cmol_c$ dm^{-3}
	Crop yield 2005/2006; 2006/2007	
----	Corn: 2,.950kg ha^{-1} Soybean: 5,027 kg ha^{-1}	Corn: 4,986 kg ha^{-1} Soybean: 2,707 kg ha^{-1}
	Average yield over last five years***	
----	Soybean: 2,873 kg ha^{-1}; Corn: 4,980 kg ha^{-1}	

(1) According to Neves et at. (2003). (2)According to Tavares Filho et al. (1999); *** SEAB (2008).

matter concentration (OM) of 23.6 g dm^{-3}, cation exchange capacity (CEC) of 6.7 $cmol_c$ dm^{-3} and pH_{H2O} of 4.7 were observed in the soil profile.

It was found that the continuous, consistent land use for 31 years had induced structural differences in the soil profiles under no-tillage (NT) and conventional tillage (CT), compared to the soil under native forest. In the case of the profile under no-tillage, a MHU was verified (Table 1) in the layer 0–0.6 m, with fissures and compact soil columns ($MHU_{F\Delta}$) with subangular polyedric structure with rough or smooth fragmentation surfaces, and pores between aggregates and biopores. Below this MHU, between 0.60 and 1.00 m, the soil structure was the same as under forest (reference – MHU_{μ}). Physical and chemical analyses (Table 1) showed a texture with a predominant clay fraction (789–800 g kg^{-1}), and Sd = 1.40 Mg m^{-3}. Besides, an OM content of 20.3 g dm^{-3}, CEC of 5.5 $cmol_c$ m^{-3} and pH_{H2O} of 5.6 were measured.

In the case of the profile under conventional tillage, a greater sub-division was observed (Table 1) due to anthropization. In the soil layer 0–0.2 m, a disaggregated MHU was verified, characterized by compact columns ($MHU_{C\Delta}$) with an angular polyedric structure as well as fine soil. Physical and chemical analyses (Table 1) indicated a texture with predominance of clay fraction (778 g kg^{-1}), and Sd = 1.21 Mg m^{-3}. Besides, an OM concentration of 8.6 g dm^{-3}, CEC of 4.8 $cmol_c$ dm^{-3} and pH_{H_2O} of 5.2 were observed. Below this structure, in the 0.2–0.5 m layer, a laminar-type MHU was found, characterized by compact columns and aggregates ($MHU_{C\Delta}$), with strong cohesion and smooth fragmentation surfaces, with no pores within and between aggregates and biopores; clay soil (800 g kg^{-1} of clay), greater soil density (1.52 Mg m^{-3}), OM concentration of 7.8 g dm^{-3}, greater acidity (pH_{H_2O} = 4.5) and CEC of 4.9 $cmol_c$ dm^{-3}. Below this layer, the soil structure was found to be the same as under forest (reference – MHU_{μ}).

All profiles were classified as very clayey (Table 1), based on a texture classification diagram (Lemos & Santos, 1984). Compared to the soil under forest (reference), the results showed that the human-influenced soil profiles studied were related to the type of agricultural management system, as follows:

- The structural modification in soil under CT was greater, with disaggregated MHU at the surface and compact MHU in the sub-surface (Bd = 1.52 Mg m^{-3}), with reduced levels of OM and CEC, and no biopores;
- Less structural modifications were observed in the soil under NT, with only one type of MHU, which was also compact (Sd = 1.40 Mg m^{-3}). Fissures and

biopores were observed, and the levels of OM and CEC were higher. The density in the NT profile was higher than reported by Roth et al. (1991) (Sd between 0.80 and 1.15 Mg m^{-3}), but similar to eth result of Tavares Filho, 1995; Tavares Filho & Tessier, 1998; Fregonezi et al., 2001; Neves et al., 2003 and Benito et al., 2008, who studied no-tillage systems in Oxisols.

Figure 1 presents the results of changes in the soil volume of samples collected from the most compact MHUs, with different soil densities (forest: MHU$_{\mu}$ Sd: 1.04 Mg m^{-3}; NT: MHU$_{F\Delta}$ (Sd: 1.40 Mg m^{-3}); and CT: MHU$_{C\Delta}$ (Sd: 1.52 Mg m^{-3}). Results of the sample analysis were described above in table 1. In all situations studied, particularly those with high water potential (Ψ > -3.2 kPa), corresponding to pores of diameter ≥ 100 μm, the values of the void ratios (e) indicated that the morphologically homogeneous unit for soil under forest (MHU$_{\mu}$) was most porous (e = 1.42), without any compaction and the air ratio (a), representing the difference between (e) and (w), was 0.29. In the case of soil under NT (MHU$_{F\Delta}$), (e) was 1.22 and the compaction resulted in a value of 0.11 for (a). For soil under CT (MHU$_{C\Delta}$), (e) was 1.14, with very compacted soil ((a) = 0.03).)

The void ratio (e) expresses the relationship between the void volume and solid volume of a soil. Accordingly, the MHU with the highest void ratio was characterized as a porous soil structure, and this explains the fact that it had the lowest soil density (Sd) value. Therefore, taking the MHU described for the soil under forest (void ratio (e) = 1.42) as a reference, it can be seen (Figure 1) that the MHU with the highest Sd in the soil under NT (MHU$_{F\Delta}$) is more porous (highest void ratio (e = 1.22)) than the MHU described with the highest Sd in the soil under CT (MHU$_{F\Delta}$) (lowest void ratio (e = 14)). This result indicates that, among the cases of highest Bd studied in the soil under NT and CT, in the soil under NT the soil particulates are still arranged in aggregates, which permits the existence of voids in the sample; on the other hand, in the case of soil under CT, the soil particulates are arranged in close contact, which results in a low void ratio and high Sd (Ribeiro et al., 2007).

Another aspect shown in figure 1 are the water and soil retention properties, in situations of MHUs with higher Sd. In the case of high potential, the void ratio decreases in the following order: Forest → NT → CT. The decreases between Forest and NT and between NT and CT are not statistically significant, but the decrease between Forest and CT is. Between the potentials -1 kPa and -1 MPa, for the three situations considered, the void ratio curve did not vary as the water ratio decreased, indicating a rigid soil for this potential range; only at values below -1 MPa the soil begins to contract as the water ratio decreases. Furthermore, in all potentials considered, the MHU is very porous in the soil under forest (reference) and, for the high water potential situations (-1 kPa to -32 kPa), is compact in the case of soil under NT the MHU$_{F\Delta}$ t, and is very compact (MHU$_{C\Delta}$) in the case of soil under CT, since the void and water ratios are the same. In terms of the water ratio curves, for the situation of high potential, the water ratio decreases in the following order: (NT = CT) → Forest; there is, however, no significant difference between the values found. These results are comparable with those of Tavares Filho, 1995; Fregonezi et al., 2001; Tavares Filho & Tessier, 1998; Neves et al., 2003; Benito et al., 2008, all of whom studied no-tillage systems in Oxisols.

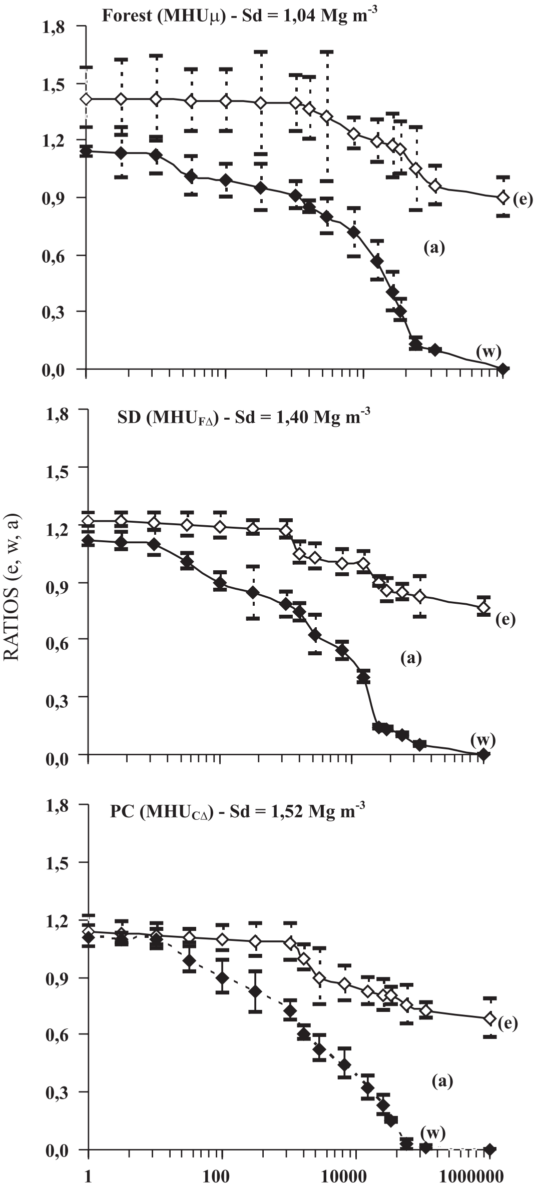

Figure 1. Evolution in the void ratio (e), water ratio (w) and air ratio [a (a = e-w)] in the different compact, morphologically homogeneous units (MHU) described (Table 1) for Oxisol profiles under forest (reference), NT (no-tillage) and CT (conventional tillage).

Figure 2 shows water drainage and retention porosity of the soil in the three situations with highest Bd values in the soil profiles studied. It is known that a major element of the soil water regime (circulation, retention, evaporation rate) is related to water retention energy. In order to classify pores according to water retention energy, it was considered that pores of diameter (Φ) $\geq$ 100 µm (-3.2 kPa) enable water circulation (water drainage) and soil aeration; pores of 100 µm (-3.2 kPa) > Φ > 0.30 µm (-1 MPa) hold plant-available water reserves; and pores of $\Phi \leq$ 0.30 µm retain water that is not available for plants.

It was found that pores of $\Phi \geq$ 100 µm account for a limited volume, compared with the other pore classes (Figure 2). This porosity, responsible for water drainage and soil aeration, decreases in the following order: Forest → NT → CT, with a significant difference both between Forest and NT and between Forest and CT, but no significant difference between NT and CT – although in the $MHU_{C\Delta}$ of the soil under CT, this pore class practically disappeared, with only 0.01 $cm^3 g^{-1}$, against 0.10 $cm^3 g^{-1}$ in the $MHU_{F\Delta}$ for the soil under NT, and 0.28 $cm^3 g^{-1}$ in the MHU_{μ} for the soil under forest. These results are comparable with those of Tavares Filho (1995) and Tavares Filho & Tessier (1998), indicating that variation in the > 100 µm pore class is a strong indication of the physical quality that these different structures (FΔ and CΔ) may represent over this long period (more than 30 years), with continuous, consistent land use. It is noteworthy that a difference of 0.01 $cm^3 g^{-1}$ in the soil total pore volume (TPV) corresponds to a volume of 10 L t^{-1} of soil, which means a reduction of 180 L of pores in soil between the situations under forest and NT, a reduction of 270 L t^{-1} of pores in soil between the situations under forest and CT, and a difference of 90 L t^{-1} of pores in soil between the situations under NT and CT, for the same period of land use. This confirms the field descriptions and results for Sd, void and water ratio curves presented above.

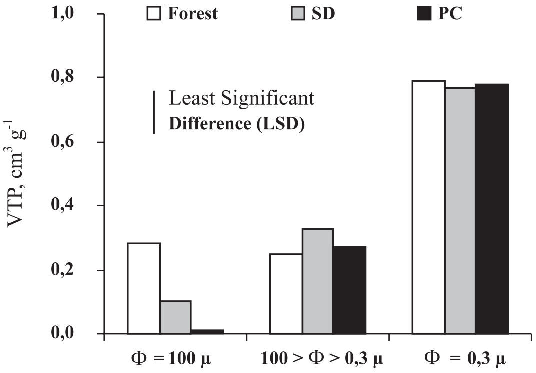

Figure 2. Total pore volume (TPV) and porosity distribution for different pore classes for the different morphologically homogeneous units (MHUs) detected in the Oxisol profiles under forest (reference), NT (no-tillage) and CT (conventional tillage).

In the pore classes of 100 µm > Φ > 0.30 µm, which hold water reserves that can be used by plants, and pores of $\Phi \leq$ 100 µm, which retain water that is not plant-available, it can be seen (Figure 2) that there were no significant differences in any situation, although in the case of plant-available water, soil under NT presented a higher absolute pore value than in the other profiles – 0.33 $cm^3 g^{-1}$, against 0.25 $cm^3 g^{-1}$ in the case of soil under forest and 0.27 $cm^3 g^{-1}$ for soil under CT. This difference of 0.06 $cm^3 g^{-1}$ in pore volume between NT and CT, with a higher value for NT, may be important in the summer, enabling plants to resist a possible water stress for a longer time. Consequently, as reported by Torres (2009), crop yield tends to be higher in areas of no-tillage than in areas under conventional tillage (Table 1). This confirms results of Cortez et al. (2009), who observed increases in corn and soybean yields over the years with the use of no-tillage systems. Carvalho et al. (2004), on the other hand, reported greater soybean yields in a year with normal precipitation in the conventional soil preparation system.

CONCLUSION

1. Under conventional tillage, the microaggregate structure of the Oxisol was disaggregated between 0 and 0.20 m, and compact (Sd = 1.52 Mg m^{-3}) in the sub-surface, between 0.20 and 0.50 m. Under no-tillage, the structure was also compact (Sd = 1.40 Mg m^{-3}) between 0 and 0.60 m; however, in this case, fissures and biopores were observed.

2. There was a limited pore volume of diameter $\geq$ 100 µm under no-tillage, whereas in the conventional management system the volume was practically non-existent. On the other hand, the pore volume in the size class of diameter < 100 µm was not affected by the type of soil management system.

LITERATURE CITED

ASSOULINE, S.; TAVARES FILHO, J. & TESSIER, D. Effect of compaction on soil physical properties: Experimental results and modeling. Soil Sci. Soc. Am. J., 61:390-398, 1997.

BENITO N.P.; GUIMARÃES M.F. & PASINI, A. Caracterização de sistemas de manejo em Latossolo Vermelho utilizando parâmetros biológicos, físicos e químicos. Semina: Ci. Agr., 29:473-484, 2008.

CARVALHO, M.A.C.; ATHAYDE, M.L.F.; SORATTO, R.P.; ALVES, M.C. & ARF, O. Soja em sucessão a adubos verdes no sistema de plantio direto e convencional em solo de Cerrado. Pesq. Agropec. Bras., 39:1141-1148, 2004.

COLLARES, G.L.; REINERT, D.J.; REICHERT, J.M. & KAISER, D.R. Qualidade física do solo na produtividade da cultura do feijoeiro num Argissolo. Pesq. Agropec. Bras., 41:1663-1674, 2006.

CORTEZ, J.W.; FURLANI, C.E.A.; SILVA, R.P. & GROTTA, D.C.C. Produção de massa por culturas implantadas em rotação no SPD de soja e milho. Available at: <www.plantiodireto.com.br> Accessed on June, 30, 2009.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA – EMBRAPA. Serviço Nacional de Levantamento e Conservação de Solo. Manual de métodos de análise de solo. Rio de Janeiro, Ministério da Agricultura, 1997. 212p.

FREGONEZI, G.A.F.; BROSSARD, M.; GUIMARÃES, M.F. & MEDINA, C.C. Modificações morfológicas e físicas de um Latossolo argiloso sob pastagens. R. Bras. Ci. Solo, 25:1017-1027, 2001.

GIAROLA, N.F.B.; TORMENA, C.A. & DUTRA, A.C. Degradação física de um Latossolo Vermelho utilizado para a produção intensiva de forragem. R. Bras. Ci. Solo, 31:863-873, 2007.

IVO, W.M.P.M. & MIELNICZUK, J. Influência da estrutura do solo na distribuição e na morfologia do sistema radicular do milho sob três métodos de preparo. R. Bras.Ci. Solo, 23:135-143, 1999.

KILASARA, M. & TESSIER, D. Intérêt des mesures physiques sur échantillons non remaniés dans la caractérisation des sols ferrallititques. Application à la couverture ferrallitique du district de Muhesa (Tanzanie) Cah. Orstom, Sér. Pédol. 26:91-103, 1991.

KLEIN, V. & LIBARDI, P.L. Faixa de umidade menos limitantes ao crescimento vegetal e sua relação com a densidade do solo ao longo do perfil de um Latossolo Roxo. Ci. Rural, 30:959-964, 2000.

LAGACHERIE, P.; COULOUMA, P.; ARIAGNO, P.; VIRAT, P.; BOIZARD, H. & RICHARD, G. Spatial variability of soil compaction over a vineyard region in relation with soils and cultivation operations. Geoderma, 134:207-216, 2006.

LAL, R. & STEWART, B.A. Soil degradation. Adv. Soil Sci., 111-345, 1990.

LEMOS, R.C. & SANTOS, R.D. Manual de descrição e coleta de solo no campo. Campinas, SBCS/SNLCS, 1984.

LESTURGEZ, G. Densification des sols sableux sous culture mécanisée. Cas du Nord-Est Thaïlandais. Nancy, Université Henri Poicaré-Nancy I, 2005. 166p. (Tese de Doutorado)

MATHIEU, C. & PIELAIN, F. Analyse physique des sols: Méthodes choisies. Paris, Lavoisier Tec & Doc, 1998. 275p.

NEVES, C.S.V.J.; FELLER, C.; GUIMARÃES, M.F.; MEDINA,C.C. & TAVARES FILHO, J. & FORTIER, M. Soil bulk density and porosity of homogeneous morphological units identified by the cropping profile method in clayey Oxisols in Brazil. Soil Tillage Res., 71:109-119, 2003.

NICOLODI, M.; GIANELLO, C. & ANGHINONI, I. Repensando o conceito da fertilidade do solo no Sistema Plantio Direto. 2007. Available at: <www.plantiodireto.com.br> Accessed on May, 29, 2008.

RIBEIRO, K.D.; MENEZES, S.M.; MESQUITA, M.G.B.F. & SAMPAIO, F.M.T. Propriedades físicas do solo, influenciadas pela distribuição de poros, de seis classes de solos da região de Lavras-MG. Ci. Agrotec., 31:1167-1175, 2007.

RICHARDS, L.A. Pressure membrane apparatus - construction and use. Agric. Eng., 28:451-454, 1947.

ROGER-ESTRADE, J.; RICHARD, G.; CANEILL, J.; BOIZARD, H.; COQUET, Y.; DEFOSSEZ, P. & MANICHON, H. Morphological characterization of soil structure in tilled fields: From a diagnosis method to the modeling of structural changes over time. Soil Tillage Res., 79:33-49, 2004.

ROTH, C.H.; CASTRO FILHO, C. & MEDEIROS, G.B. Análise de fatores físicos e químicos relacionados com a agregação de um Latossolo Roxo distrófico. R. Bras. Ci. Solo, 15:241-248, 1991.

SECRETARIA DA AGRICULTURA E DO ABASTECIMENTO DO PARANÁ – SEAB. Estimativa de safra. Available at: <www seab.pr.gov.br> Accessed on Dez. 20, 2008.

TAVARES FILHO, J. & TESSIER, D. Influence des pratiques culturales sur le comportement et les propriétés de sols du Paraná (Brésil). Étude Gestion Sols, 5:61-71, 1998.

TAVARES FILHO, J. Organisation et comportement des Latosols du Paraná (Brésil). Influence de leur mise en valeur. Nancy, Université Henri Poicaré-Nancy I, 1995. 229p. (Tese de Doutorado)

TAVARES FILHO, J.; RALISCH, R.; GUIMARÃES, M.F.; MEDINA, C.C.; BALBINO, L.C. & NEVES, C.S.V.J. Método do perfil cultural para avaliação do estado físico de solos em condições tropicais. R. Bras. Ci. Solo, 23:393-399, 1999.

TAVARES FILHO, J.; BARBOSA, G.M.C.; GUIMARÃES, M.F. & FONSECA, I.C.B. Resistência do solo à penetração e desenvolvimento do sistema radicular do milho (*Zea mays*) sob diferentes sistemas de manejo em um Latossolo Roxo. R. Bras.Ci. Solo, 25:725-730, 2001.

TAVARES FILHO, J.; GRIMALDI, M. & TESSIER, D. Compressibilidade de agregados de um Latossolo Amarelo da Amazônia em resposta ao potencial da água do solo.R. Bras. Ci. Solo, 29:489-495, 2005.

TESSIER, D. & BERRIER, J. Utilisation de la microscopie életronique à balayage dans l'étude du sol. Observation de sols humides soumis à différents pF. Sci. Sol, 1:67-82, 1979.

TORRES, E. ENCONTRO COCAMAR DE PRODUTORES DE SOJA: RESPOSTA PARA A ESTIAGEM ESTÁ NO MANEJO DO SOLO, 7., 2009. Available at: <www.cocamar.com.br/Portal/cooperado> Accessed on June 30, 2009.

VIEIRA, M.J. Embasamento técnico do subprograma de manejo e conservação do solo. In: PARANÁ. Secretaria da Agricultura. Paraná Rural: Programa de Desenvolvimento Rural do Paraná: Manual técnico do subprograma de manejo e conservação do solo. Curitiba, 1989. p.12-40.