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Physical and hydraulic properties of a Latosol influenced by land use and management changes

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Changes to soil use can modify the soil's physical and hydraulic properties, affecting its potential for productivity. This study aimed to characterize the physical and hydraulic properties of a clayey Dystroferric Red Latosol under the following land uses: conventional tillage (CT), direct drilling systems (DD), and native forest (NF). The study was conducted in Londrina (PR), Brazil, (23°23′ S, 50°11′ W and altitude of 585 m). Soil samples were collected at depths of 0 to 0.10, 0.10 to 0.20, 0.20 to 0.30, and 0.30 to 0.40 m. The following properties were evaluated: size distribution of solid particles, particle density, soil bulk density, total porosity, macroporosity, microporosity, water infiltration, and soil water retention curve. Conventional tillage and DD of this land modified soil physical and hydraulic properties from that under NF. The NF soil had greater organic matter content in its surface layer, a greater number of macropores, lower density, and less water retention capacity than soils from the CT and DD systems. At a precipitation rate of 70 mm h^{-1}, only the CT system exhibited surface run-off. This was due to rupturing of the porous system and a lower infiltration rate. In contrast, plant residues in the DD system protected the soil structure against damage caused by direct impact due to raindrops, allowing for total infiltration of simulated rainfall events. The NF soil is important in extracting and replenishing groundwater stores. However, it does not retain more water than the other systems in the surface layers.

Key words: Soil water retention, soil water infiltration, direct drilling system, Dystroferric Red Latosols, conventional tillage.

INTRODUCTION

The state of Paraná in Brazil underwent a period of great change in land use starting at the beginning of the twentieth century. This period saw the replacement of native forests by agricultural lands (Gubert Filho, 1998). The removal of plant cover and adopting unsuitable soil management practices with intensive cultivation

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considerable accelerated the erosion and compaction process, resulting in the degradation of agricultural soils because of a rapid decline in organic matter content (Castro Filho and Logan, 1991). The change in ground cover also triggered changes to water balance, causing reduced water infiltration rates and increasing surface runoff, in addition to increasing evaporation and reducing transpiration.

Rates of water infiltration into soil, along with the hydraulic conductivity of saturated soils, are two of the most important physical properties used to understand accelerated erosion. Water infiltration into the soil profile is considered a property that controls leaching, runoff and crop water availability (Franzluebbers, 2002). Portable rainfall simulators are useful to measure infiltration rates in the field (Roth et al., 1985; Santos et al., 2016). Thus, determining the infiltration rate plays a crucial role, given the direct relationship between erosion and ability of water to infiltrate and move into deeper layers of the soil profile (Roth et al., 1985).

The direct drilling (DD) system has often been recommended as a soil management technique for tropical and subtropical climates. This is due to the accumulation of surface residues and tilling only the sowing line, which supports higher carbon content in surface soil (Calegari et al., 2006). Furthermore, permanent plant cover at the soil surface provided by this agricultural system favors the physical conditions necessary for seed germination and initial crop growth (Vanlauwe et al., 2014). The use of green manure has the potential to improve soil chemistry, as well as its biological and physical properties (Zaccheo et al., 2016). In addition to plant cover, seeders equipped with drilling shafts in direct drilling systems provide a physical environment beneficial for establishing crops by increasing total porosity, macroporosity, and by reducing soil bulk density and mechanical resistance to penetration in the sowing line (Nunes et al., 2014). In direct drilling systems, straw mulches applied to the soil surface improves soil water status, reduces hydraulic gradients and soil temperature during the growing season by providing an insulation layer, especially in the period of crop establishment (Siczek et al., 2015). In contrast, where conventional tilling is part of soil preparation, there is a reduction in organic matter content and soil macroporosity compared with forest and DD soils (Dalmago et al., 2009).

Soil bulk density at the surface layer may increase in the years following DD implementation, which is due to soil compaction caused by the machinery used to conduct growing operations (Secco et al., 2005). As organic matter levels and biological activities increase, however, soil structure improves while soil bulk density gradually decreases (Assis and Lanças, 2005). The water available for crop cultivation largely determines the level of climate risk. Soils with high organic matter content provide better conditions for profile rooting and exploitation, resulting in greater yields in non-irrigated conditions. The volume of water stored in soil tends to be greater at higher (more positive) potentials when planted without tilling in forest soils and becomes lesser as the potential declines (Dalmago et al., 2009). The aim of this work was to characterize the physical and hydraulic properties of a Dystroferric Red Latosol after conventional tillage and direct drilling, and compare it to soil in native forest.

MATERIALS AND METHODS

This study was conducted at the Experimental Station of the Agronomic Institute of Paraná (IAPAR) in Londrina (PR), Brazil, (23°23′ S and 50°11′ W), where the altitude was 585 m. The region has a Cfa climate type, which according to Köppen classification, is described as humid and subtropical with hot summers. The average annual temperature is 21.1°C. The temperature during the hottest (January) and coldest (July) months are 23.9 and 16.9°C, respectively. The average annual precipitation is 1,610 mm. December, January, and February are the wettest months, while June, July, and August receive the least rainfall (Caviglione et al., 2000).

The soil at the study area is described as a clayey Dystroferric Red Latosol according to the Brazilian soil classification system (Santos et al., 2013). It is similar to a Ferralsol (Food and Agriculture Organization of the United Nations - FAO, 2006), and a very fine, ferruginous, isothermic rhodic happludox according to USDA Soil taxonomy (Soil Survey Staff, 1998). Additional details regarding the mineralogical and chemical characteristics were reported by Castro Filho and Logan (1991). In all three soil management types, particle size composition exhibited clay levels greater than 75 dag kg^{-1} throughout the soil profile (Table 1). Conventional tillage (CT) uses one operation with disc plough at a depth between 20 and 25 cm and two disking with the light disc harrow for leveling the ground and preparing the seedbed. This area was maintained for 10 years by cultivating winter cover crops black oats (*Avena strigosa* Schieb), oil seed radish (*Raphanus sativus* L. var. Oleiferus Metzg), or white lupins (*Lupinus albus* L.). In the summer, it was seeded with black mucuna (*Mucuna pruriens*) and *Crotalaria spectabilis*. During the flowering stage, cover crops were treated with herbicides while the soils were broken up and then smoothed using a harrow. The area was kept uncovered and weeded by hand to collect physical and hydraulic data. To determine soil-physical hydric properties, the area was cleaned with hand hoeing weeding.

The direct drilling system (DD) area was, for 8 years, maintained with soybean with an inter-row spacing of 0.5 m during the summer, and black oats (IAPAR Ibiporã 61 variety) with an inter-row spacing of 0.17 m during the winter. The seeder for direct drilling was equipped with narrow tires, which opened a narrow slot into the mulch-covered soil. This equipment was pulled using a medium tractor according to National Association of Motor Vehicle Manufacturers (ANFAVEA, 2011) classification, New Holland®, model TL 75, 4 × 2 TDA with 78 horse power). This tractor was equipped with 12.4 to 24 front tires (0.31 m) with a diagonal structure and 18.4 to 30 rear tires (width: 0.47 m). The native forest (NF) comprised two hectares in a secondary mixed hardwood with a highly diverse flora that was maintained as a legal reserve. Soil samples were collected using a Dutch auger. This was to determine the total organic carbon content in each of the three systems (DD, CT, and NF). Samples were taken from four different depths (0 to 0.10 m, 0.10 to 0.20 m, 0.20 to 0.30 m, and 0.30 to 0.40 m), with three replicates for each. The samples were carbon oxidized by wet

Table 1. Particle size distribution of Dystroferric Red Latosol at four depths under a conventional tillage system (CT), a direct drilling system (DD), and in a native forest (NF) in Londrina (PR), Brazil.

Land uses / Soil managements	Depth (m)											
	0 – 0.10			0.10 – 0.20			0.20 – 0.30			0.30 – 0.40		
	Clay	Silt	Sand	Clay	Silt	Sand	Clay	Silt	Sand	Clay	Silt	Sand
	--- dag kg^{-1} ---			--- dag kg^{-1} ----			--- dag kg^{-1} -			--- dag kg^{-1} -		
CT	78	17	5	76	17	7	77	16	7	79	14	7
DD	79	15	6	82	11	7	81	12	7	81	12	7
NF	76	14	10	76	14	10	77	13	10	79	13	8

combustion with potassium dichromate (Walkley and Black, 1947). Data analysis was conducted according to the methods reported by Pavan et al. (1992). To conduct physical and hydraulic analyses, undisturbed soil samples were collected in between the rows after the summer harvest and/or following the management of undergrowth plants and before sowing winter species. For this purpose, trenches were dug in March 2011 and soil samples were collected horizontally and then were inserted in the soil, using Köpecky cylinders of 0.05 m height and internal diameter with sharp edges and an internal volume of 98.17 cm^3.

Soil particle density was determined using the volumetric flask method. Soil bulk density, total porosity, macroporosity, and microporosity were determined using methods described by EMBRAPA (1997). Soil samples were weighed and placed on a suction table measuring 0.32 m × 0.54 m × 0.10 m, which was protected by a screen and parchment paper for 48 h. The height of the water column was set to obtain a matrix potential of -6 kPa. The samples were then returned to the table and adjusted to obtain a matrix potential of -10 kPa and until the weight was constant. The samples were then weighed and placed on ceramic plates inside a Richard's pressure chamber set at potentials of -33, -100, -300, -500, and -1,500 kPa. This was for drainage and to obtain soil moisture retention curves. Soil water retention curves were obtained by adjusting the soil's volumetric water content (θ, in cm^3 cm^{-3}) and the soil matrix potential (ψm, - kPa). Soil water retention curve modeling was carried out using the computer program, Soil Water Retention Curve (SWRC), version 3.0 beta (Dourado Neto et al., 2001). A constraint (m = 1 – 1/n) (Mualem, 1976) was applied to the model we used, which was first proposed by Mualem-Genuchten (van Genuchten, 1980) (Equation 1):

$$\theta = \theta_s + \frac{\theta_s - \theta_r}{[1+(\propto.\Psi_m)^n]^m} \quad (1)$$

where θ is the volumetric soil water content (cm^3 cm^{-3}), θ_{sat} is saturated soil water content (cm^3 cm^{-3}), θ_{res} is the residual soil water content (cm^3 cm^{-3}) at a matrix potential equal to 1,500 kPa (van Genuchten 1980; Pires et al., 2008); α, n, and m are adjustment parameters for the equation. The water available at a depth range of 0.0 to 0.04 m was calculated as the difference between the water retained in the soil samples at a matrix potential of -10 kPa and -1,500 kPa (Silva et al., 2006). Soil bulk density, total porosity, macroporosity, microporosity, and soil organic carbon content were all analyzed statistically. All experiments were conducted according to a randomized block design, with split-plots and four replicates. Land uses and soil management (of DD, CT and NF were considered the main factor, while sampling depths (0 to 0.10 m, 0.10 to 0.20 m, 0.20 to 0.30 m, and 0.30 to 0.40 m) were used as the split-plot. The results were analyzed using an analysis of variance (ANOVA), with an F-test at 95% probability. Means were compared using Tukey's test. All statistical analyses were performed using Sisvar software, version 5.1 (Ferreira, 2011).

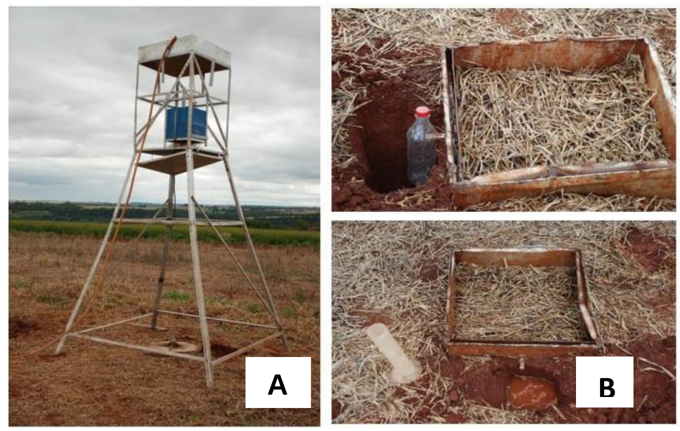

Figure 1. Portable rainfall simulator (A) and galvanized steel sheet collector (B).

Water infiltration and water loss in the three land use systems was evaluated in March 2011 using a portable rainfall simulator developed by Roth et al. (1985), which was installed at a height of 3 m. The simulator was calibrated for rainfall of 70 mm h^{-1} for 60 min. The infiltration index was calculated as the difference between rainfall intensity and surface runoff. The terrain slope at the three sites was approximately 2%.

A 0.12 m^2 sheet of galvanized steel was dug into the soil at a depth of 0.25 m to perform the procedure. The metal sheet was comprised of a gutter and a spout to collect surface runoff into a test tube at 2 min intervals. Three measurements were taken at different sampling points at each of the land use types (Figure 1).

RESULTS AND DISCUSSION

Soil samples from the CT and DD sites exhibited higher bulk densities and microporosity (Figure 2a and 2d), as well as lower total porosity and macroporosity, than samples from NF (Figure 2b and 2c). This was at the four depths tested. At a soil depth of 0 to 0.1 m, our results were similar to those reported by Pagliai et al. (2004) for a soil submitted to ripper equipment or minimum tillage compared to conventional tillage. They observed that soil macroporosity (pores with effective diameter greater than 50 μm) at a depth of 0 to 0.1 m in conventionally tilled soil was lower than soils under minimum tillage or ripper

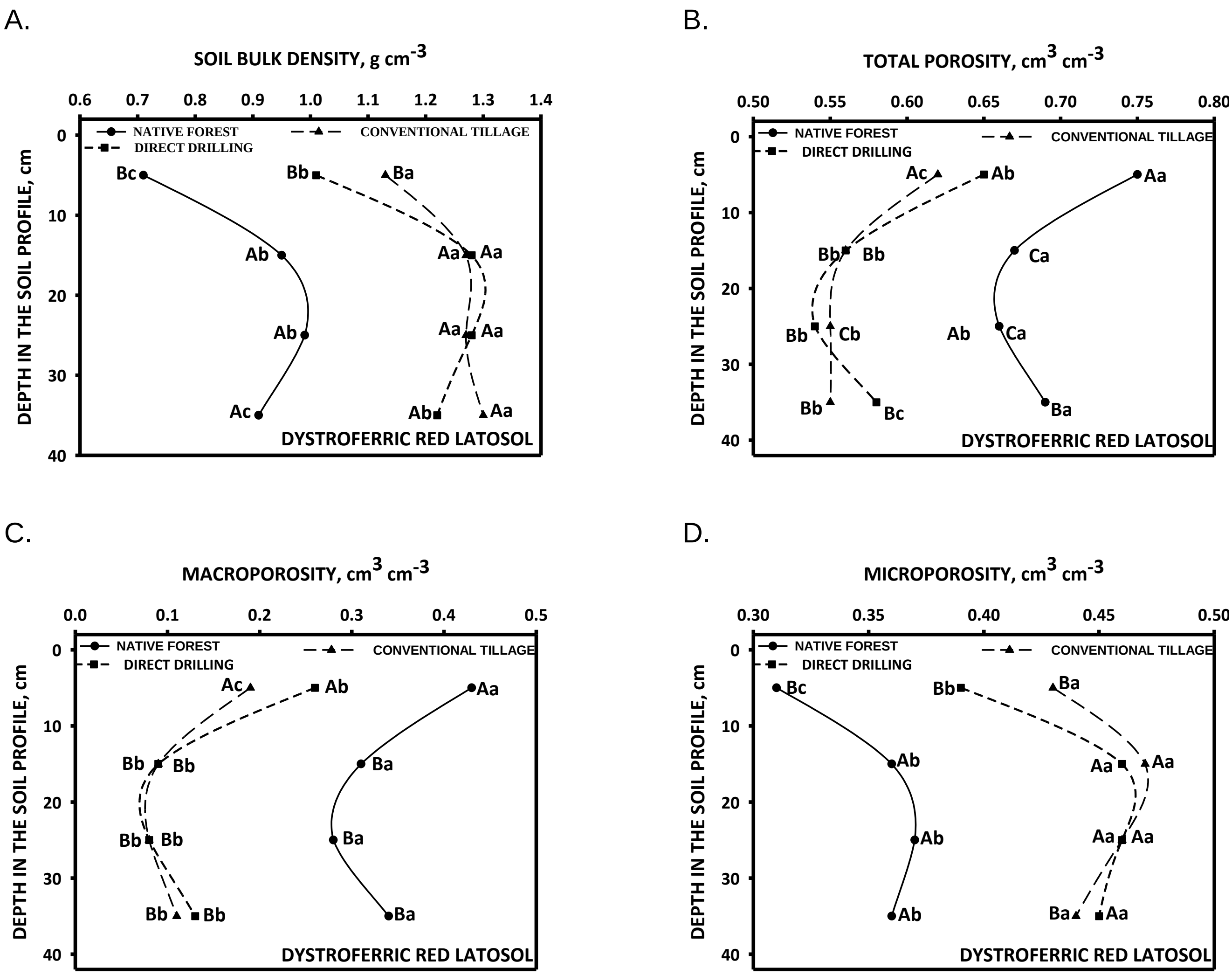

Figure 2. Physical properties of the clayey Dystroferric Red Latosol under different uses and management types at four depths: (0.0-0.10 m; 0.10-0.20 m; 0.20-0.30 m; 0.30-0.40 m). A: soil bulk density; B: total porosity; C: macroporosity and D: microporosity. Means followed by the same lower case letters (within the same soil depth compared among land uses) and upper case letters (within land uses compared among different soil depths) were not significantly different according to Tukey's test ($p > 0.05$).

sub soiling. Minimum disturbance of soil at this depth could improve its physical properties, which can be beneficial for root growth and the mechanical actions of the seeder.

As suggested earlier by Derpsch et al. (1991) for this tropical clayey Latosol, soil bulk densities greater than 1.25 g cm^{-3} could restrict root growth, aeration and water permeability. Other criteria, which could be adopted for classifying soil physical conditions, are based on pore size distribution (Pagliai et al., 2004). These authors have also shown that a more developed surface crust in conventionally tilled soils may cause a decrease in soil porosity. In addition, the soils in this system are prone to soil compaction and subsurface plough pan.

Based on the afore-mentioned criteria, soil layers ranging from 0.1 to 0.2 m and 0.2 to 0.3 m under CT and DD are compacted and are therefore considered not favorable to root growth and water distribution in the soil profile. Despite changes to soil physical properties being possibly related to soil structure damage, the higher microporosity in those soils could be the result of an increase to available water for plants (Sidiras and Vieira, 1984; Derpsch et al., 1991; Pagliai et al., 2004).

It is likely that the physical and hydraulic properties of Dystroferric Red Latosol following CT are more subject to changes imposed by land management compared to the DD system. This is consistent with observations reported by Sidiras and Vieira (1984). These authors reported that CT soil was more susceptible to variations in soil bulk density caused by tractor wheels during sowing. These results are related to lower structure stabilization and to the soil load-bearing capacity of soils subjected to conventional tillage (Dias Junior and Pierce, 1996). At depths of 0 to 0.10 m and 0.30 to 0.40 m, soil bulk density, total porosity, and macroporosity were not considered as constraints to plant growth and water infiltration into the soil. This was despite soil bulk density values in the surface layer increasing by 34% under DD conditions, when compared to NF soil, and by 42% under CT conditions (Figure 2). In clayey Dystroferric Red Latosol with reduced tillage and CT, Argenton et al. (2005) reported there were increased soil bulk densities between 71 and 86% for depths ranging from 0.05 to 0.10 m, and between 10 and 16% for depths ranging from 0.30 to 0.40 m. Machine use and unsuitable soil moisture conditions lead to permanent damage to the soil structure (Dias Junior and Pierce, 1996). This is the result of the pressure applied to the ground surface (Argenton et al., 2005) by tires or active parts of the equipment that exceed the soil's ability to withstand the weight (Silva et al., 2003). Such heavy weights are transmitted to various depths through stress distribution (Araujo-Junior et al., 2011). Soil bulk density increase of 27 and 37% were recorded after applying an equivalent amount of pressure (900 kPa) on samples of oxidic-gibbistic red yellow latosol and clayey kaolinitic yellow latosol (Silva et al., 2006).

In two clayey Oxisols (81 and 83 dag kg^{-1} clay) of the West region of the State of Paraná, Brazil, Assouline et al. (1997) reported that soil compaction differed when subjected to compressions ranging from 50 kPa to 1,000 kPa. Those researchers also showed that beyond the similarity in particle size distribution and soil bulk density of both soil types, there were several differences in their physicochemical properties, particle thickness and crystallinity, all of which affect soil stability. In addition to changes in soil bulk density, Silva et al. (2006) reported there was a reduction in the average diameter of stable aggregates in water. This was at a total porosity volume of 17 and 23%, reflecting reductions in macroporosity by 53 and 67%, and increases in microporosity by 35 and 23%, respectively, for yellow red latosol and yellow latosol in samples subjected to 900 kPa. In the present study, the reduction in total porosity at depths ranging from 0.0 to 0.10 m, when compared to NF soil (0.75 cm^3 cm^{-3}), was 14% for soil under the DD system (0.65 cm^3 cm^{-3}) and 18% (0.62 cm^3 cm^{-3}) under the CT system (Figure 2). At a depth range of 0.0 to 0.10 m, the sowing of winter undergrowth plants and commercial plants in the summer in CT and DD systems may have positively changed their physical properties based on the seeder's active parts (circular blade, sowing drill, fertilizer dispensers, seed sowing drill, and tamping wheel). In addition, there was an accumulation of plant residues and land preparation through plowing and using a harrow.

Sowing both summer and winter crops may contribute to favorable structural conditions at the surface of DD soils (Nunes et al., 2014). Another aspect worth mentioning is that the pressure exerted by these parts of the seeder may change the pressure applied to the sowing layer, as noted by (Reis et al., 2006), for compacting components. Furthermore, Reis et al. (2006) noted that the sowing shaft reduced the soil bulk density from 1.14 kg dm^{-3} to 1.00 kg dm^{-3} at a maximum depth of 8.0 cm. The low soil bulk densities observed in the NF (Figure 2a) may be due to the thick layer of undergrowth that has been deposited over the years, making the NF surface soil levels highly organic and porous (Assis and Lanças, 2005; Centurion et al., 2007). Greater total porosity values (macro and microporosity) at a depth range of 0.0 to 0.15 m in CT soils compared with DD in Dystroferric Red Latosol were observed by Silva and Rosolem (2001). The effect of the undergrowth on the physical properties of the soil is cumulative and requires years of management before a significant difference become apparent (Laurani et al., 2004). In the present study, the DD system was used for eight consecutive years and already showed changes in the soil's surface levels. In the CT system, with management incorporating winter cover crops, such as black oats cultivar Iapar 61 used as green manure, improvements and differences in the soil's properties were not very pronounced in comparison to those in the DD system. Forest soil contained higher total organic carbon content than that found in agricultural soils at depths of 0.0 to 0.10 m and 0.10 to 0.20 m (Figure 3). This may be attributed to greater organic residue provided by the tree canopy, in addition to the interception of incident radiation, which minimizes oxidation of the soil's organic matter by directly radiating the soil surface. Conventional tillage promoted a mean decrease of 43% in soil organic carbon content at soil surfaces of 0 to 0.10 m (Figure 3). Due to the short duration under DD (8 years), no differences were observed in the organic carbon content in the soil compared to CT.

At a depth range of 0.20 to 0.30 m, the total organic carbon content observed in the soil under the CT system was similar to that observed in the NF and greater than that of DD soil. This may have been the result of soil layer inversion caused by soil preparation in the CT system, which distributes carbon to greater depths, increasing organometallic bonds and reducing microbial decomposition. The CT system introduced more carbon than the DD system in the layers evaluated as a result of crop rotation that incorporates undergrowth plants. Similar results, with respect to the total organic carbon content of the soil, were reported by Argenton et al. (2005), who confirmed that the association of cover crops with corn, stabilized the carbon content at certain depths regardless of the management system (DD or CT). It was expected that over the years, the DD system will gradually increase the carbon content in the soil profile because of the cumulative effect of adding plant residues to the surface layers, thereby improving the soil's physical properties (Calegari et al., 2006). The results of the adjustment parameters using the Mualem-Genuchten

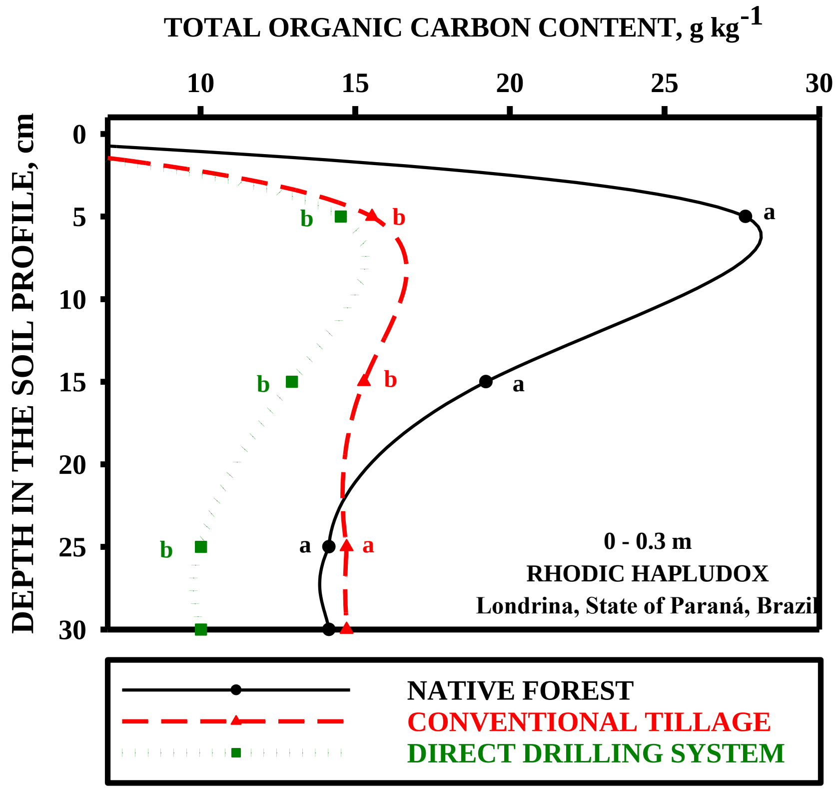

Figure 3. Total organic carbon content of a clayey Dystroferric Red Latosol under the following land uses and management types: conventional tillage system (CT) and direct drilling system (DD). These were compared to native forest (NF) soil. Samples were taken at three depths. Means followed by the same lower letter within the same depth were not significantly different according to Tukey's test ($p > 0.05$).

model for the water retention curves for the LVdf in native forest and different soil management systems are presented in Table 2. The model was adjusted to the data, with a coefficient of determination (R^2) between 0.87 and 0.99, all of which were significant at 1% ($P < 0.01$) probability according to the F-test.

Soil water retention curves from the three environments at four depths are displayed in Figure 4. At a depth range of 0.0 to 0.10 m, it was observed that CT soil provided greater water retention values among the potentials, ranging from -0.32 kPa to -1,500 kPa. Soil porosity was modified by CT soil preparation (reducing total porosity and macroporosity, while increasing microporosity) (Figure 2). With regards to NF soil (□v–10 kPa = 0.2973 cm^3 cm^{-3}), the Dystroferric Red Latosol's water retention rate, at a matrix potential equal to -10 kPa (field capacity) under the CT system (□v–10 kPa = 0.4026 cm^3 cm^{-3}) increased by 30%. The DD system (□v–10 kPa = 0.3761 cm^3 cm^{-3}), however, increased by 20% in relation to water retention at -10 kPa when compared with NF soil. On the other hand, the CT system increased the water retention rate by 6% relative to the DD system (Figure 4). This result was also observed by Sidiras and Vieira (1984), who noted that a modification of the porous space in the traffic line of an 85 HP tractor showed a positive effect on the ability of the soil to retain water. A similar effect was observed when growing wheat, soybeans, and turnips, relative to the soil between the wheel tracks, because pore volumes were reduced if their diameters were greater than 10 µm.

In the 0.10 to 0.20 m layer, NF soil retained less water at all matrix potentials, when compared to soil from CT and DD systems (Figure 3). Due to the increased macropore volume and low soil bulk density (Figure 2), these physical and hydraulic properties do not contribute to water storage. In the 0.30 to 0.40 m layer, there was greater water retention at less negative potentials than in the other environments. Nevertheless, the total volume of water retained in the NF was less at all depth ranges, which bolsters the forest's role in maintaining soil quality, providing water absorption, preventing run-off, replenishing the groundwater table, and recycling water via transpiration. Furthermore, the possibility that forest soil at the higher depths could hold more water should not be discarded. However, these measurements were not evaluated in the present study. The volume of

Table 2. Parameters of the model Mualem-Genuchten after adjusting water retention curves by the clayey Dystroferric Red Latosol under different land uses and at different depths.

Parameters	0.0 - 0.10	0.10 - 0.20	0.20 - 0.30	0.30 - 0.40
	Native Forest Soil, NF depth (m)			
θ_{sat} (cm^3 cm^{-3})	0.67	0.63	0.59	0.65
θ_{res} (cm^3 cm^{-3})	0.19	0.26	0.28	0.25
α (kPa^{-1})	9.89	3.32	1.73	3.07
N	1.33	1.41	1.47	1.43
M	0.25	0.29	0.32	0.30
R^2	0.98	0.99	0.98	0.99
F Value	1,126.45	3,858.83	1,032.65	2,795.00
Significance (%)	< 0.001	< 0.001	< 0.001	< 0.001
	Conventional Tillage Soil, CT depth (m)			
θ_{sat} (cm^3 cm^{-3})	0.56	0.55	0.53	0.54
θ_{res} (cm^3 cm^{-3})	0.28	0.36	0.35	0.35
α (kPa^{-1})	1.19	0.41	0.45	0.48
N	1.31	1.46	1.40	1.62
M	0.24	0.31	0.29	0.38
R^2	0.92	0.87	0.88	0.94
F Value	214.03	156.03	169.42	355.80
Significance (%)	< 0.001	< 0.001	< 0.001	< 0.001
	Direct Drilling Soil, DD depth (m)			
θ_{sat} (cm^3 cm^{-3})	0.62	0.52	0.52	0.54
θ_{res} (cm^3 cm^{-3})	0.26	0.33	0.34	0.34
α (kPa^{-1})	3.52	0.30	0.38	0.63
N	1.32	1.36	1.34	1.39
M	0.24	0.26	0.25	0.28
R^2	0.97	0.97	0.97	0.97
F Value	686.85	559.36	642.81	840.61
Significance (%)	< 0.001	< 0.001	< 0.001	< 0.001

θ_{sat} = volumetric soil water content at saturation (cm^3 cm^{-3}), θ_{res} = volumetric residual soil water content (cm^3 cm^{-3}) at a matrix potential of 1,500 kPa (van Genuchten, 1980, Pires et al., 2008); α, n, and m are adjustment parameters for the equation with its limitations. The R^2 corresponds to the coefficient of determination. The F value was calculated for the equation.

available water varied between 9 and 12% at all depths, which was similar to values (9 and 10%) reported by Faria and Caramori (1986) for the same soil under CT conditions. The volume of water stored in the soil profile at a maximum depth of 0.40 m was greater under DD conditions (42 mm) and lower in the forest (38 mm), whereas soil under CT provided 39.71 mm of storage.

Soil-water infiltration

Surface runoff in the NF and DD environments did not occur following 60 min of precipitation at intensity of 70 mm h^{-1}. In contrast, runoff from the CT environment was observed. This was attributed to the distribution of solid particles in the soil, which were quantified by increased soil bulk density values and changes to the porous system (a reduction in the total porous volume and macroporosity) (Figure 2). Following the three rain simulation events, the CT environment experienced a loss of water totaling 24.1 mm, 11.5 mm, and 24.0 mm, respectively. The ground cover in the CT environment was between 2 and 3%, whereas that of the DD environment was approximately 80 to 90%. In an area composed of the same Dystroferric Red Latosol under the DD system, and without plant coverage, water infiltration was constant for up to 10 min after simulating rain at an intensity of 68 mm h^{-1} (Roth et al., 1985). It was noted that after 60 min of rain, water infiltration decreased to 5 mm h^{-1}. Nevertheless, it is clear that plant cover in the DD system is efficient at providing better conditions for water infiltration into soils, thus, preventing

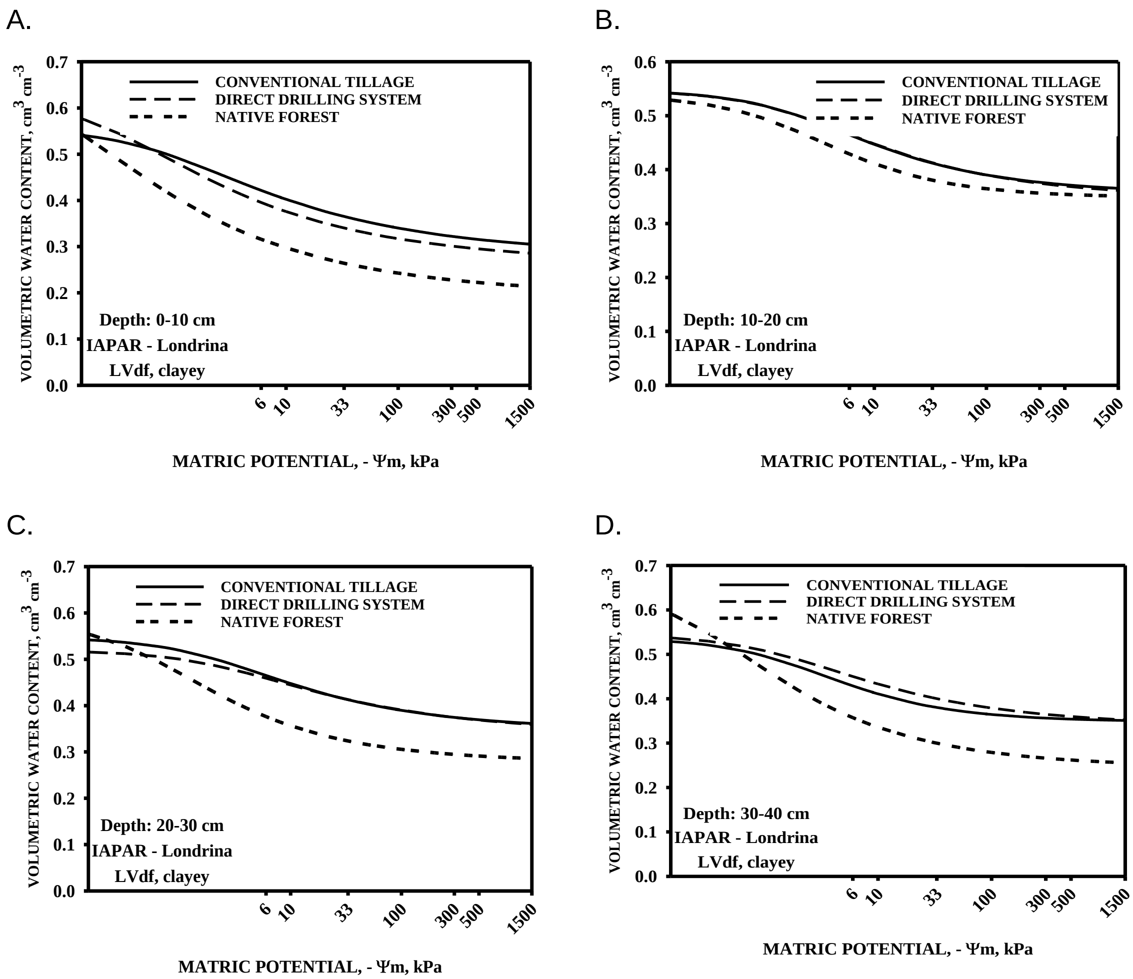

Figure 4. Water retention curves for the Dystroferric Red Latosol in a conventional tillage system (CT), a direct drilling system (DD), and a native forest (NF) in Londrina (PR), Brazil, at depths of 0.0–0.10 m (A), 0.10–0.20 m (B), 0.20–0.30 m (C), and 0.30–0.40 m (D).

erosion and contributing to increased water storage and the replenishment of groundwater. The presence of organic matter in the surface NF soil profile reduced soil bulk density and increased macroporosity, thus, reducing its ability to retain water at a maximum depth of 0.40 m (Franzlubbers, 2002; Araujo-Junior et al., 2011). On the one hand, those researchers suggested that the particle density of organic matter was considerably lower than that of mineral soil. On the other hand, in both NF soil and DD soil, total water infiltration occurred at an intensity of 70 mm h^{-1}, whereas that of the CT demonstrated surface runoff.

Insufficient surface undergrowth of the CT system's soil leads to the formation of surface level crusting. This is a surface layer of variable thickness created by the disaggregation of soil by water droplets, resulting in reduced water infiltration (Sidiras and Vieira, 1984, Araujo-Junior et al., 2011, 2015). In a test that simulated rain at an intensity of 85 mm h-1 on the same Dystroferric Red Latosol used in this study, Araujo-Junior et al. (2015) showed that water infiltration can be reduced to 7 mm h^{-1} in areas with insufficient plant cover. This result reinforces the fundamental role that plant cover plays in maintaining the physical and hydraulic properties of surface level tropical soils, as well as in the replenishment of springs and in precipitation recycling, also enabling the total infiltration of precipitated water and the exit of water through transpiration.

Conclusion

1. Soil use in CT and DD systems lead to changes in the physical and hydraulic attributes of the soil, thus, increasing soil bulk density and microporosity, reducing total porosity volume and macroporosity beneficial for water movement by the clayey Dystroferric Red Latosol in relation to native forest soil.

2. The CT system maintained total organic carbon content at 0.20 to 0.30 m depth similar to that observed in NF and greater than that of DD.
3. Permanent soil cover in the DD system, proportioned by plant residues, protected the soil structure against damage caused by direct impact of raindrops, maintained soil bulk density lower than critical limits, total porosity, macroporosity and enhanced water infiltration compared to conventional tillage soil.

Conflict of Interests

The authors have not declared any conflict of interests.

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