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PHYSICAL-HYDRAULIC PROPERTIES OF AN ULTISOL UNDER NO-TILLAGE AND CROP-LIVESTOCK INTEGRATION IN THE CERRADO[1]

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ABSTRACT - Light soils are more susceptible to degradation and need to be exploited in a conservational manner, thus avoiding rapid degradation. The objective of this study was to evaluate the physical-hydraulic properties of an Ultisol under no-tillage and crop-livestock integration in the Cerrado of eastern Maranhão state, Brazil. The evaluated managements were one area under no-tillage system for fourteen years (soybean/ millet) and three areas with different histories of adoption of the crop-livestock integration (CLI) system under no-tillage (soybean/millet), with the difference being: times of entry with CLI (2, 4 and 8 years), as well as a native Cerrado area, considered a control. Soil collection was carried out in June 2018 at depths of 0.00-0.10, 0.10-0.20, 0.20-0.30 and 0.30-0.50 m. Disturbed and undisturbed samples were collected to determine the following variables: bulk density, porosity, resistance to penetration, retention curve and available water capacity. Data were subjected to the calculation of means and confidence intervals (95%). The area with a recent history of crop-livestock integration showed better density, porosity, resistance to penetration, water storage capacity and available water. No-tillage for fourteen years leads to high resistance to penetration, less porosity and low water storage capacity. The integrated system (CLI) improves the quality of the physical-hydraulic properties and the values found are similar to those observed in an area under native vegetation.

Keywords: Water in the soil. Soil resistance. Integrated systems.

PROPRIEDADES FÍSICO-HÍDRICAS DE UM ARGISSOLO SOB PLANTIO DIRETO E INTEGRAÇÃO LAVOURA-PECUÁRIA NO CERRADO

RESUMO - Os solos leves possuem maior suscetibilidade ao processo de degradação e necessitam ser explorados de forma conservacionista, evitando assim sua rápida degradação. Objetivou-se com o estudo avaliar as propriedades físico-hídricas de um Argissolo sob plantio direto e integração lavoura-pecuária no Cerrado da região leste do estado do Maranhão. Os manejos avaliados foram uma área sob sistema de plantio direto há quatorze anos (soja/milheto) e três áreas com diferentes históricos de adoção do sistema de integração lavoura-pecuária (ILP) sob plantio direto (soja/milheto), sendo a diferença os tempos de entrada com ILP (2, 4 e 8 anos), além de uma área de cerrado nativo, considerado testemunha. A coleta do solo foi realizada em junho de 2018 nas profundidades de 0,00-0,10; 0,10-0,20; 0,20-0,30; 0,30-0,50 m. Foram coletadas amostras deformadas e indeformadas, para determinação das variáveis: densidade do solo, porosidade, resistência à penetração, curva de retenção e capacidade de água disponível. Os dados foram submetidos ao cálculo das médias e de intervalo de confiança (95 %). A área com histórico recente de integração lavoura-pecuária apresentou melhor densidade, porosidade, resistência a penetração e capacidade de armazenamento e água disponível. O plantio direto há quatorze anos apresenta alta resistência a penetração, menor porosidade e baixa capacidade de armazenamento de água. O sistema integrado (ILP) melhora a qualidade das propriedades físico-hídricas, sendo o sistema com maior capacidade de água disponível para as plantas.

Palavras-chave: Água no solo. Resistência do solo. Sistemas integrados.

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INTRODUCTION

The Cerrado of eastern Maranhão, specifically in the Chapadinha microregion, is located in the Brazilian agricultural frontier known as MATOPIBA, acronym of the States of Maranhão, Tocantins, Piauí and Bahia, with soybean as the main cultivated crop (ALMEIDA et al., 2019). In this region, light-textured Ultisols occupy 5.8 million hectares (LUMBRERAS et al., 2015) and are considered more susceptible to degradation and loss of production capacity when compared to soils of finer texture in similar environments (DONAGEMMA et al., 2016).

In addition, the light Ultisols of eastern Maranhão also have a cohesive nature (RESENDE et al., 2014) and hence are even more vulnerable to degradation as the presence of the dense subsurface horizon leads to low water infiltration, resulting in recurrent removal of the surface soil layer by erosion. In cohesive soils, the relationship between soil physical attributes and the management used is one of the prerequisites necessary to define appropriate practices for their exploitation (RIBEIRO et al., 2016), because agricultural activities promote changes in soil attributes that can further compromise their physical conditions and the sustainability of their use.

In this context, the best way for the agricultural exploitation of these soils is through conservation management, such as no-tillage and integrated systems, which are managements that contribute to soil preservation and quality (COSER et al., 2018). Some studies have shown that integrated systems improve soil physical quality by increasing porosity and water retention and reducing density and resistance to penetration (BONETTI et al., 2015).

Thus, it is indispensable, especially in light and cohesive Ultisols, to study soil physical-hydraulic properties that include variables such as bulk density, porosity, resistance to penetration, water retention curve and available water capacity, commonly used in the evaluation of management systems, as they make it possible to assess soil compaction, structure and water storage (BONETTI et al., 2019; DIONIZIO; COSTA, 2019). Furthermore, these attributes are important and influence other soil properties such as fertility, as well as crop development and yield.

Therefore, considering the scarcity of research, the objective of this study was to evaluate the physical-hydraulic properties of an *Argissolo Amarelo Distrocoeso típico* (Ultisol) with ‘arenic’ (sandy) characteristic under no-tillage and crop-livestock integration in eastern Maranhão, Brazil.

MATERIAL AND METHODS

The study was carried out in the municipality of Brejo, eastern region of the Maranhão state, Brazil (03º42’0.93” S and 42º56’25.57” W). The altitude ranges from 100 to 400 m, with undulating to gently undulating relief. The climate of the region, according to Köppen’s classification, is hot and humid tropical (Aw) with rainy season from November to April. The average annual temperature is higher than 27 °C with average precipitation of 1,835 mm (Figure 1). The soil of the area is classified as *ARGISSOLO AMARELO Distrocoeso típico* (Ultisol) with predominance of kaolinite mineralogy (DANTAS et al., 2014).

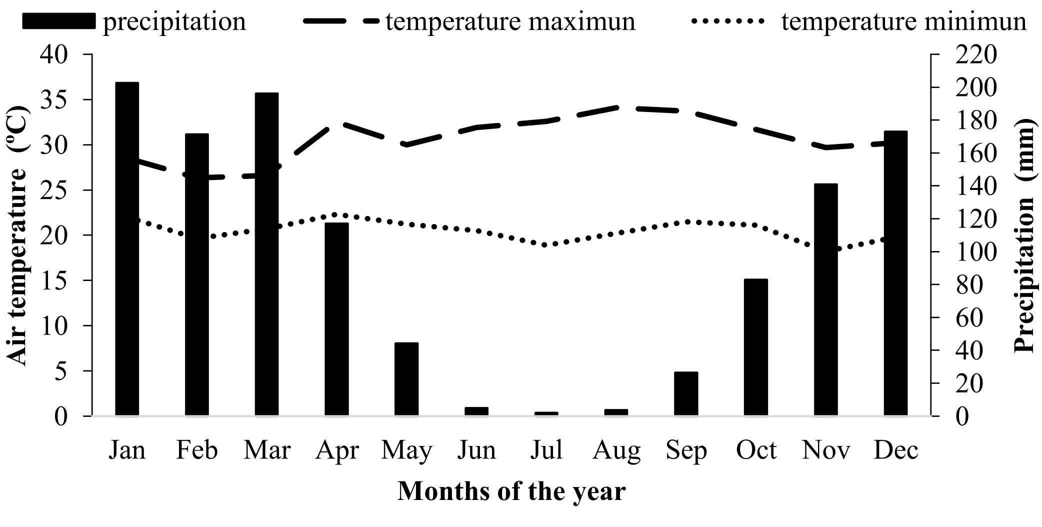

Figure 1. Historical series of climatic data between 1976 and 2017 of the studied region.

One area under exclusive use in no-tillage and three areas under no-tillage with different histories of adoption of crop-livestock integration were chosen, in addition to an area under native Cerrado vegetation (Table 1).

Table 1. Description and history of the studied areas.

Description	History
NT14 No-tillage for 14 years	No-tillage system: opening of the area in 2003 with soil turning (plowing and harrowing) and incorporation of 2 t ha^{-1} of limestone. First year of cultivation in 2004 with soybean, and the following years with no-tillage (soybean - 1st season and millet - 2nd season) until 2018. Fertilization was performed based on the recommendation for soybean crop.
NT-CLI8 No-tillage, once under crop-livestock integration for eight years	No-tillage system with history equal to that of NT14 until 2009. In 2010 the area was turned (plowing and harrowing), received 3.7 t ha^{-1} of calcitic limestone and was managed in a crop-livestock integration system [maize + pasture (*Brachiaria ruziziensis*) with entry of 0.7 animal unit per hectare in the off-season]; in the following year and until 2018 the area returned to management under no-tillage (soybean and millet). Fertilization was performed based on the recommendation for soybean and maize crops.
NT-CLI4 No-tillage, once under crop-livestock integration for four years	No-tillage system, with a history of use and management equal to that of NT14 until 2009; in 2010 there was soil turning (plowing and harrowing) and incorporation of 3.7 t ha^{-1} of limestone; in 2014, the area was used under crop-livestock integration system [maize + pasture (*Brachiaria ruziziensis*) with 0.8 animal unit per hectare in the off-season]; in the following years until 2018 the area was again used under no-tillage system (soybean and millet). Fertilization was performed based on the recommendation for soybean and maize crops.
NT-2CLI No-tillage, twice under crop-livestock integration	No-tillage system with history equal to that of NT14 until 2011; in 2012 the area was turned (plowing and harrow) and received 3.8 t ha^{-1} of calcitic limestone with adoption of crop-livestock integration [maize + pasture (*Brachiaria ruziziensis*) with 1.5 animal units per hectare in the off-season]; from 2013 to 2015 the area was managed under no-tillage system (soybean and millet); in 2016 the area was subsoiled up to 0.30 m and again with adoption of the crop-livestock integration system [maize + pasture (*Brachiaria ruziziensis*) with 0.8 animal unit per hectare in the off-season]; in the following years the area was again used under no-tillage system (soybean and millet). Fertilization was performed based on the recommendation for soybean and maize crops.
Forest Native vegetation	Area under native vegetation of Cerrado Biome, considered as a reference of non-anthropized area.

Soil sampling was carried out by opening in each area four mini pits, measuring 0.60 x 0.60 x 0.60 m, spatially distributed at a distance of fifty meters from each other, to collect disturbed and undisturbed soil samples. Samples with preserved structure were collected using volumetric aluminum rings of 0.025 m diameter and 0.05 m height, taken in the center of each layer evaluated. Disturbed samples were taken in number of eight replicates around each soil pit (3.0 m apart).

Soil samples were collected in the 0.00-0.10, 0.10-0.20, 0.20-0.30 and 0.30-0.50 m layers. After collection, undisturbed samples were packed on plastic film for soil and moisture preservation and, with the disturbed samples, they were analyzed.

Soil total porosity (TP), macroporosity (Macro), microporosity (Micro) and bulk density (BD) were determined according to Teixeira et al. (2017).

Soil water retention curves (WRC) were fitted with data obtained after determination of soil porosity, initially saturating the undisturbed samples and subjecting them to matric potentials (Ψm) of -2, -4, -6, -10, -33, 126 -100, -300, - 500 and -1500 KPa in Richards' pressure plate apparatus, fitted based on the mathematical model proposed by Van Genuchten (1980).

Available water capacity (AWC) was calculated by the product of the difference of moisture obtained in the Richards' pressure plate apparatus between the Ψm of field capacity for sandy soils (-10 kPa) and the wilting point (-1500 kPa), by the soil layer depth.

Disturbed samples were analyzed as described in Teixeira et al. (2017) for total organic carbon (TOC) obtained by sulfuric digestion and soil particle size (Table 2), by the pipette method.

Soil resistance to penetration (RP) was determined according to Stolf (1991) using an impact penetrometer, IAA/Planalsucar model, by penetrating a metal rod into the soil from ten impacts to each of the four replicates per area, up to 0.50 m depth.

Table 2. Mean values of the particle-size composition of the soil of the studied areas.

Use and management	Particle size (g kg^{-1})				
	Sand			Silt	Clay
	Coarse	Fine	Total		
			0.00 – 0.10 m layer		
NT-2CLI	455	326	781	50	169
NT-CLI4	402	320	722	100	178
NT-CLI8	415	342	757	59	184
NT14	346	367	713	141	146
Native forest	174	574	748	78	174
			0.10 – 0.20 m layer		
NT-2CLI	476	307	783	25	192
NT-CLI4	355	352	707	154	139
NT-CLI8	379	348	727	70	203
NT14	413	311	724	91	185
Native forest	333	371	704	112	184
			0.20 – 0.30 m layer		
NT-2CLI	437	289	726	56	218
NT-CLI4	378	329	707	64	229
NT-CLI8	379	336	715	62	223
NT14	327	371	698	89	213
Native forest	306	37	680	86	234
			0.30 – 0.50 m layer		
NT-2CLI	398	288	686	102	212
NT-CLI4	356	283	639	104	257
NT-CLI8	318	331	649	101	250
NT14	336	337	673	113	214
Native forest	268	396	664	100	236

With the data, the statistics used to compare the areas were represented by the calculation of means and confidence intervals (95%), according to Pimentel-Gomes and Garcia (2002); the variables in each layer were compared individually, and the similarity was identified by the overlap of the confidence intervals (PAYTON; MILLER; RAUN, 2000).

RESULTS AND DISCUSSION

Soil organic carbon (TOC), in the 0.00-0.20 m layer, was higher with the recent adoption of the NT-2CLI and NT-CLI4 systems, when compared to the other land uses under study (Table 3). Considering the other soil layers evaluated, the adoption of crop-livestock integration system (2, 4 and 8 years) led to higher TOC concentration compared to that observed in the area under no-tillage for 14 years.

Bulk density (BD) values were higher than 1.50 Mg m³ among the studied areas and layers (Table 3). The highest value of BD (1.75 Mg m^{-3}) observed in NT14 did not exceed the reference value for soils with predominance of sand particle size (1.75 Mg m^{-3}), which can limit the root system of plants (REINERT et al., 2008). Bulk density is dependent on the time of adoption of the no-tillage system; however, in many cases, this type of management increases BD and the increment can be observed up to the depth of 0.50 m (BLANCO-CANQUI; RUIS, 2018).

The area under no-tillage system for fourteen years had lower values of TP and Macro for all studied layers. The lower value of porosity found in NT14 was higher than 10%, which is considered by Bengough et al. (2011) as the minimum value for oxygenation of the root system of plants. The reduction of porosity found in NT14 is probably related to the occurrence of compacted layers, formed by the combination of the pressure exerted by machinery traffic and absence of soil turning over the fourteen years. The traffic of agricultural machinery in the no-tillage system reduces total porosity and macroporosity and increases bulk density; however, over the years the negative effects decrease. In the present study according to the data presented, after fourteen years of adoption of the NT system, there were no improvements in the attributes TP and Macro, observed in the surface layer of the soil as recommended by Reichert et al. (2016).

Table 3. Mean values of physical attributes and confidence interval (95 %) of an Ultisol under conservation management systems in Brejo, MA, Brazil.

Land use	TOC	BD	Soil porosity			RP
			TP	Macro	Micro	
	g kg^{-1}	Mg m^3	---------------------------- % ----------------------------			MPa
			0.00 – 0.10 m layer			
Forest	13.2±0.8	1.50±0.05	38.6±1.0	21.0±2.0	17.6±1.3	0.74±0.17
NT-2CLI	16.9±0.8	1.59±0.07	42.2±1.3	18.9±1.2	23.3±2.3	1.38±0.12
NT- CLI4	17.4±1.1	1.55±0.10	41.5±0.7	19.9±0.6	21.6±1.1	1.44±0.05
NT-CLI8	16.0±0.7	1.60±0.06	36.1±2.0	19.2±2.5	16.9±0.9	1.49±0.02
NT14	14.2±0.8	1.68±0.02	32.2±1.2	15.8±0.2	16.5±1.4	1.54±0.03
			0.10 – 0.20 m layer			
Forest	13.6±0.8	1.59±0.06	37.8±0.6	20.6±0.9	17.2±0.3	1.26±0.17
NT-2CLI	16.8±0.5	1.62±0.11	38.8±1.2	20.±1.4	18.2±1.7	1.84±0.13
NT- CLI4	17.4±1.0	1.75±0.06	36.1±1.6	20.5±3.0	15.6±1.6	2.36±0.12
NT-CLI8	15.3±1.0	1.75±0.05	30.8±0.9	16.4±0.5	14.4±0.6	1.97±0.07
NT14	14.3±0.4	1.73±0.04	33.3±3.7	18.2±2.8	15.1±5.0	2.13±0.15
			0.20 – 0.30 m layer			
Forest	10.9±1.9	1.59±0.05	36.8±1.5	19.1±0.1	17.7±0.5	1.69±0.18
NT-2CLI	14.0±0.7	1.55±0.06	37.2±0.6	19.2±1.0	18.0±0.7	2.23±0.11
NT- CLI4	14.6±0.9	1.62±0.07	34.2±2.3	18.3±1.5	15.9±0.9	2.55±0.05
NT-CLI8	13.5±1.4	1.69±0.05	32.0±2.6	17.2±1.9	14.7±0.8	2.51±0.03
NT14	12.2±1.5	1.73±0.04	31.2±0.5	16.6±0.5	14.6±0.2	2.70±0.13
			0.30 – 0.50 m layer			
Forest	10.8±0.8	1.62±0.07	33.7±0.9	16.6±0.9	17.1±0.5	1.54±0.07
NT-2CLI	12.0±0.7	1.63±0.07	37.4±0.6	19.5±0.1	17.8±0.6	2.43±0.25
NT- CLI4	13.9±1.5	1.68±0.09	35.0±3.4	18.5±1.8	16.5±1.6	2.48±0.08
NT-CLI8	12.0±1.0	1.69±0.07	30.1±1.5	15.3±0.5	14.9±1.0	2.57±0.02
NT14	11.2±0.2	1.66±0.05	31.6±2.4	16.4±1.6	15.2±0.8	2.51±0.01

NT-2CLI = no-tillage area, twice under crop-livestock integration and subsoiled in 2016; NT-CLI4 = no-tillage area, once under crop-livestock integration system for four years before soil collection; NT-CLI8 = no-tillage area once under crop-livestock integration system for eight years before soil collection; NT14 = area under no-tillage with soybean/millet for fourteen years without soil turning and entry of animals; Forest = area under native Cerrado vegetation. BD = bulk density; TP = total porosity; Macro = macroporosity; Micro = microporosity.

However, the higher porosity observed in NT-2CLI is due to the higher organic matter content indicated by the TOC content (Table 3), and the justification for this result are the intercropping of Brachiaria with maize and effect of the pasture root system. In soils compacted by machine traffic, forage grasses can break the hardened layer (FLÁVIO NETO et al., 2015). In this context, Brachiaria stands out as a species capable of recovering soil structure (SILVA et al., 2019a), with the distribution of the root system being facilitated by subsoiling (HE et al., 2019), improving physical properties in compacted soils.

Microporosity was also influenced by the type of management, and the highest values of this variable (Table 3) were observed in the area where the adoption of the integration system was more recent (NT-2CLI and NT-CLI4). The results indicate that there is a greater number of intra-aggregate pores capable of retaining water, attributed to the organic matter content, important in the formation of soil aggregates, which arise as a result of energy and matter flows between the components of the production system (CUNHA NETO et al., 2018).

However, in the present study, due to the history of the adoption of the systems and type of soil management, when evaluating the behavior of RP up to the 0.20 m depth layer, it is observed that the highest value was found in the area under no-tillage for fourteen years and the lowest value in the area under no-tillage with adoption of CLI and subsoiling practice (NT-2CLI), which was around 0.50 MPa lower than that observed in area NT14 (Table 3, Figure 2).

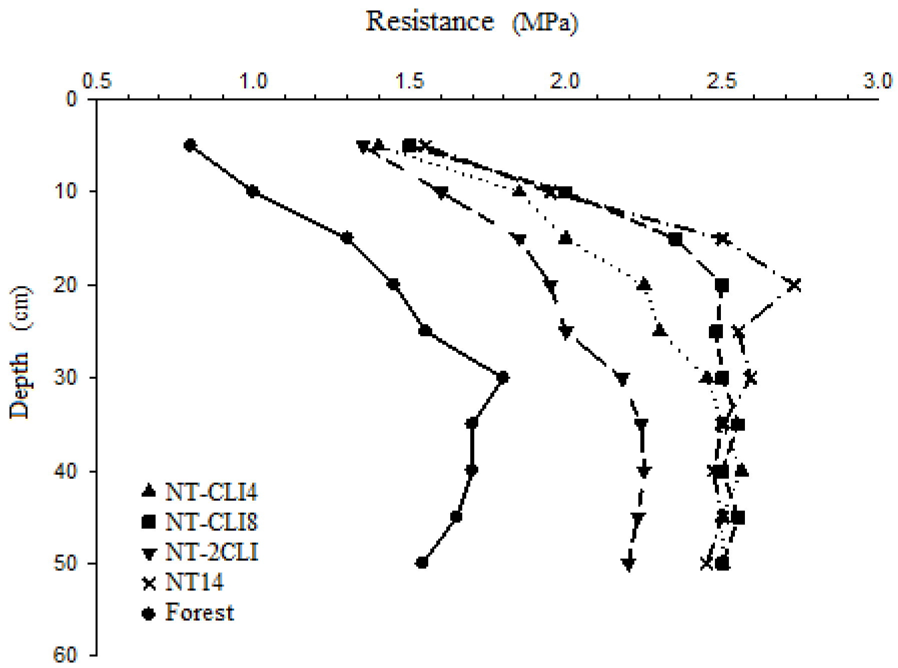

Figure 2. Resistance to penetration of an Ultisol under different conservation management systems, Brejo, MA, Brazil. No-tillage area, twice under crop-livestock integration (NT-2CLI); no-tillage area, once under crop-livestock integration system for four years (NT-CLI4); no-tillage area once under crop-livestock integration system for eight years (NT-CLI8); no-tillage area for fourteen years (NT14), area under native Cerrado vegetation (Forest).

Cortez et al. (2019), when evaluating the variability of resistance to penetration in a soil under long-term no-tillage, observed an increase in the RP value, which reached 4.0 MPa with the increase in soil depth, reaching a maximum level at 0.25 m.

Below the 0.20 m layer there was a reduction in RP in the area under NT14, but it remained high with a value of around 2.5 MPa, which was also observed in NT-CLI8 at 0.25 m and in NT-CLI4 around 0.30 m depth. In the area NT-2CLI in subsurface, the RP values were higher than 2.0 MPa below 0.30 m depth. In cohesive soils, the analysis of RP can show the degree of cohesion along the soil profile (LIRA et al., 2016). The RP value found in subsurface layers in both NT-2CLI and the other areas under agricultural use and management is above 2.0 MPa, which is considered as limiting value of RP, capable of reducing root growth.

Along the soil profile, it can be observed that the soil under native vegetation had the lowest RP value, which was 0.8 MPa lower than the highest value observed in the subsurface layer of 0.30 m observed in NT14. The lower RP values observed in the forest area are attributed to the absence of anthropic intervention, maintaining under natural condition the physical properties of the soil in this environment.

The lower RP values observed in the area under NT-2CLI may be associated with the recent subsoiling, making the soil profile more conducive to the exploitation by the root system of the crops used for grain and pasture production, and thus making it better structured compared to other managements, in addition to the recent use of Brachiaria, which acts as a conditioner in the improvement of soil physical attributes.

It is worth pointing out that the lower RP observed both in the Forest area and in NT-2CLI is also due to higher soil moisture content (Table 4), in addition to the lower BD observed, variables that directly influence soil resistance to penetration (OLIVEIRA et al., 2019).

The highest available water capacity (AWC) was observed in the areas of NT-2CLI and Forest (Table 3). It is likely that the higher AWC found in NT-2CLI and in the forest is related to the quantity and quality of organic matter present in the soil, supplied by the diversity of crops used more than once in the NT-2CLI area and by the natural vegetation in the forest area.

According to Parihar et al. (2016), the accumulation and maintenance of organic matter from the vegetation cover favor the physical and structural quality of the soil, contributing to water infiltration especially when the soils have high contents of the sand fraction.

Figures 3 (A, B, C and D) show the water retention curves (WRC) of the studied soil evaluated at four depths under different systems of use and management. The results reveal that soil water retention was influenced by the type and time of land use and management adopted.

Table 4. Mean values of moisture content in an Ultisol under different conservation management systems, Brejo, MA, Brazil.

Layer (m)	Use and management				
	NT-2CLI	NT-CLI4	NT-CLI8	NT14	Forest
	kg kg^{-1}				
0.00 – 0.20	0.14	0.12	0.12	0.12	0.13
0.20 – 0.50	0.13	0.12	0.12	0.12	0.14

NT-2CLI = no-tillage area, twice under crop-livestock integration and subsoiled in 2016; NT-CLI4 = no-tillage area, once under crop-livestock integration system four years before soil collection; NT-CLI8 = no-tillage area once under crop-livestock integration system for eight years before soil collection; NT14 = area under no-tillage with soybean/ millet for fourteen years without soil turning and entry of animals; Forest = area under native Cerrado vegetation.

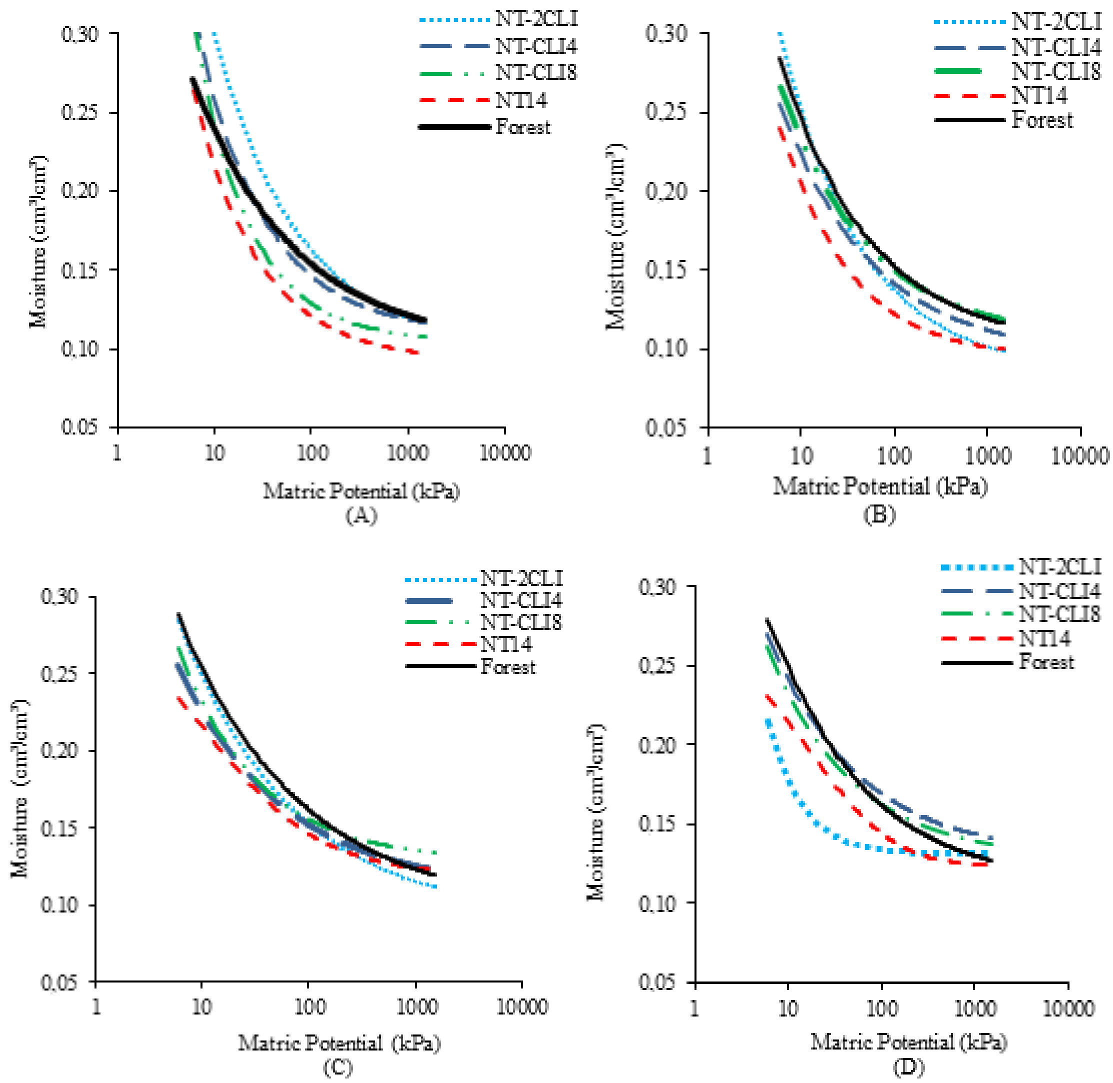

Figure 3. Water retention curves of an Ultisol under different conservation management systems, evaluated at four depths (A: 0.00-0.10 m; B: 0.10-0.20 m; C: 0.20-0.30 m; and D: 0.30-0.50 m), Brejo, MA, Brazil. No-tillage area, twice under crop -livestock integration (NT-2CLI); no-tillage area, once under crop-livestock integration system for four years (NT-CLI4); no-tillage area once under crop-livestock integration system for eight years (NT-CLI8); area under no-tillage for fourteen years (NT14), area under native Cerrado vegetation (Forest).

The NT-2CLI area obtained high water retention at all tensions in the surface layer (0.00-0.10 m), followed by NT-CLI4 and NT-CLI8, and the lowest retention was observed in NT14. At this depth, the soil under native vegetation had intermediate water retention capacity compared to those observed in the areas under no-tillage that adopted the crop-livestock integration system.

Silva et al. (2019b) report that integrated systems increase soil organic matter content, assisting in water storage, even in drought periods, minimizing impacts caused by water stress. Thus, considering the climatic conditions (Figure 1) in the soil sampling period, it is possible to note the importance of adopting the CLI system for the soil water content in the areas NT-2CLI, NT-CLI4 and NT-CLI8.

In the forest area, the value of organic matter content was lower than that observed in areas with a history of CLI; however, it is believed that the results found for WRC should be associated with the presence of biopores capable of retaining water, which are formed by the diversified root system of natural vegetation and the action of the more abundant soil fauna.

The lowest water retention observed up to the 0.30 m layer was found in the NT14 area, which is related to lower organic matter content, porosity and higher bulk density (Table 3).

In the 0.30-0.50 m layer, the highest water retention at low tensions was observed in the forest area; however, with increased tensions, greater water retention was verified in NT-CLI4 and NT-CLI8. At this depth, the area under NT-2CLI obtained lower water retention capacity, probably due to the higher content of sand (coarse sand). In sandy soils, as in the present study, the increase in matric potential promotes rapid emptying of pores, so the amount of moisture that remains in the soil is lower (DEXTER, 2004).

The mean values of the fitting parameters, and the coefficient of determination of the WRCs (θs, θr, α, m, n and r^2) referring to the studied land use and management systems are presented in Table 5. The fit of the retention curves showed a coefficient of determination (r^2) above 97% for all areas studied, indicating a good relationship between the water content in the soil and the matric potential evaluated.

Table 5. Empirical parameters of the Van Genuchten model for soil water retention curves in the studied areas.

Use and management	Parameters					
	θs	θr	α	m	n	r^2
	m^3 m^{-3}					
	Depth (0.00 – 0.10 m)					
NT-2CLI	0.419	0.101	0.245	0.057	8.901	0.982
NT-CLI4	0.407	0.110	0.305	0.080	7.633	0.989
NT-CLI8	0.349	0.105	0.213	0.055	13.552	0.978
NT14	0.330	0.092	0.276	0.091	6.910	0.999
Forest	0.339	0.101	0.374	0.059	6.946	1.000
	Depth (0.10 – 0.20 m)					
NT-2CLI	0.378	0.085	0.305	0.066	7.555	0.978
NT-CLI4	0.323	0.095	0.370	0.068	6.379	0.991
NT-CLI8	0.290	0.106	0.222	0.041	11.098	0.988
NT14	0.304	0.094	0.288	0.193	3.076	0.999
Forest	0.360	0.101	0.357	0.085	6.946	0.999
	Depth (0.20 – 0.30 m)					
NT-2CLI	0.357	0.091	0.359	0.064	6.297	0.985
NT-CLI4	0.329	0.110	0.422	0.083	5.241	0.998
NT-CLI8	0.315	0.128	0.281	0.070	8.042	0.992
NT14	0.312	0.119	0.100	0.992	0.785	0.999
Forest	0.363	0.096	0.394	0.056	6.791	1.000
	Depth (0.30 – 0.50 m)					
NT-2CLI	0.357	0.131	0.346	0.500	2.500	0.988
NT-CLI4	0.329	0.129	0.360	0.070	6.304	0.997
NT-CLI8	0.305	0.128	0.297	0.062	7.624	0.993
NT14	0.316	0.124	0.004	4.630	0.551	0.997
Forest	0.333	0.112	0.283	0.173	2.560	0.999

NT-2CLI = no-tillage area, twice under crop-livestock integration and subsoiled in 2016; NT-CLI4 = no-tillage area, once under crop-livestock integration system four years before soil collection; NT-CLI8 = no-tillage area once under crop-livestock integration system for eight years before soil collection; NT14 = area under no-tillage with soybean/ millet for fourteen years without soil turning and entry of animals; Forest = area under native Cerrado vegetation. θs = saturation soil moisture; θr = residual soil moisture; α, m, n = model fitting parameters.

The highest residual soil moisture content (θr) was observed in the subsurface layer of 0.30-0.50 m in all evaluated areas. The result found may be related to the presence of the dense horizon characteristic of cohesive soils, usually found between 0.30 and 0.70 m, where the presence of cryptopores, pores in which water can remain retained with very high energy, is common (KLEIN; LIBARDI, 2002).

CONCLUSIONS

No-tillage system combined with crop-livestock integration adopted in cohesive and arenic soils of the Cerrado region of eastern Maranhão is more efficient in improving the physical quality of the soil than the exclusive use under no-tillage.

The use of the crop-livestock integration system in an area under no-tillage for more than once promotes an increase in water storage capacity and water availability for crops, being only 2.65% lower than the available water capacity observed in soils under native Cerrado vegetation.

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