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SOIL SCIENCE

Physical-hydric attributes in Latossolo Amarelo under systems of use in the Cerrado/Caatinga ecotone areas in Piauí State, Brazil

DJAVAN P. SANTOS, THIAGO R. SCHOSSLER, ISIS L. DOS SANTOS, NATHÁLIA B. MELO, JÚLIO CÉSAR A. NÓBREGA & GLENIO G. SANTOS

Abstract: The Cerrado/Caatinga transition region in Piauí State has a high potential for production of food, fiber and energy, representing about 19% of the total area of the State. This work aimed to evaluate physical and hydraulic attributes under different crops in Latossolo Amarelo Distrófico (Oxisol) in cerrado/caatinga transition areas, in the Southwest of Piauí. In this study five areas with different crops were evaluated as follows: areas under pasture crop with *Andropogon gayanus* grass with three and six years of crop, area under intensive crop of *Pennisetum purpureum* grass, area under orchard of *Annona squamosa* L., area under intensive crop irrigated with central pivot and area under native vegetation of cerrado/caatinga ecotone representing a condition of equilibrium. Soil attributes evaluated were: soil density, total porosity, macroporosity, microporosity, unsaturated pores, blocked pores, saturation humidity, effective saturation, water readily available, void index, mechanical resistance of soil and saturated field hydraulic conductivity. The intensive crop of napier grass for five consecutive years and the pivot irrigated area under intensive crop for four years presented the greatest negative impacts on soil density, total porosity, macroporosity, saturation humidity, effective saturation, water readily available and index of voids.

Key words: Hydraulic conductivity, soil density, soil penetration resistance, management systems.

INTRODUCTION

The Cerrado/Caatinga ecotone areas in Piauí present high potential for grains, pastures, irrigated fruit and fiber, etc. Geographically, these areas represent 47,790.51 km^2 approaching 19% of the total area of the State and are located along a strip between the Center-East and the valley of Baixo and Médio Parnaíba and between Alto Parnaíba and Southeast of State (Farias & Castro 2004). Due to its distinct characteristics in relation to Cerrado and Caatinga biomes, the evaluation of cropping, land use and management systems should be prioritized in this portion of land in order to select the best practices that contribute to improve and/or maintain the quality of the soils.

In this way, the evaluation of production systems associated to the use of conservation practices for the Cerrado/Caatinga ecotone areas is of extreme economic and environmental importance. Due to the proximity of these areas with the region known today as Matopiba, associated to the valorization of the lands in Piauí Cerrado (Dantas & Monteiro 2011) and the repeated problems of climatic irregularities (Campos et al. 2014), there has been migration of part of the production for the ecotone areas, naturally with soils of lower agricultural potential than cerrado soils.

The soil physical-hydric attributes such as density, porosity, hydraulic conductivity, water retention characteristic (WRC) (Balbino et al. 2004), soil resistance to penetration (Marchão et al. 2007) and the optimal water range (Silva et al. 2017), have been commonly used as soil physical quality indicators in different regions of Brazil, due to the relative ease of determination and the low cost of obtaining the measures. In addition to comparisons between crop types, land use and management systems, physical-water attributes have also been used to study the effect of conversion of native areas into crops or pastures (Marchão et al. 2007, Santos et al. 2011).

When studying the physical behavior of a Latossolo Amarelo Distrófico in Cerrado of Piauí, Fontenele et al. (2009) found higher values of soil density and lower values of infiltration rate in cultivated areas compared to native cerrado vegetation. Pragana et al. (2012) observed that the main differences between cultivated Latossolos Amarelos and native Cerrado were demonstrated by the variables soil density, total porosity and macroporosity, which explained the higher percentage of variation among the studied areas. Still, according to Silva et al. (2017), the conversion of the native cerrado to two-year conventional tillage, six- and twelve-year-old eucalyptus resulted in a lower physical-hydraulic attributes change in Latossolo Amarelo Distrófico.

The aim of this study was to evaluate the physical-hydraulic attributes of Latossolo Amarelo Distrófico under different systems of use in the Cerrado/Caatinga ecotone, in Southwest region of Piauí.

MATERIALS AND METHODS

The study was carried out at the University Campus of the Federal University of Piauí (UFPI), in the town of Bom Jesus-PI (09° 04' 48'' S, 49° 19' 35 '' W, altitude 290 m). The climate is warm and semi-humid type Aw, with annual average temperature of 30 °C and annual average rainfall of 1,100 mm, with the rainier quarter from December to February (INMET 2018). The six soil profiles of the experimental areas were all classified as Latossolo Amarelo Distrófico (Oxisol), according to the discretion presented in the Brazilian Soil Classification System (EMBRAPA 2018) and the average values of particle size distribution and textural grouping of each area are described in Table I.

In the study, five soil use systems (Table II) were evaluated, as follows: pasture with *grass andropogon* (AG3 and AG6, with three and six years of use, respectively), pasture with *grass napier* (PP), *Annona squamosa* L. (AS), area under intensive crop of cowpea and irrigated corn with central pivot (IC) and area under native vegetation of ecotone cerrado/caatinga (NV), considered a reference area of study.

In each area of crop and native vegetation, soil samples were collected at the midpoint of each layer, in three mini-trenches, arranged in a transect in direction of greater length of the area, in the 0-0.10 layers; 0.10-0.20; 0.20-0.30 and 0.40-0.50 m depth. In each soil layer, three undisturbed samples were taken in stainless steel volumetric rings of 5.1 cm in height and 5.0 cm in diameter (95 cm^3), which amounted 12 samples per area. The samples were collected between December 2011 and January 2012. Likewise for the determination of humidity, particle size distribution and soil particle density, deformed samples were collected and added in plastic bags identified and taken immediately to the laboratory for specific measurements,

Table I. **Particle size distribution of the soil particles and grouping texture in the area under grass andropogom three years of use (GA3), grass andropogom six years of use (AG6), Napier grass (PP) until orchard of *Annona squamosa* L. (AS) pivot with crop intensive study of cowpea and irrigated maize with central pivot (IC) and native vegetation (NV), in southwestern Piauí.**

Areas	Particle size distribution				Textural grouping
	Clay	Silt	Coarse sand	Fine sand	
	(g kg^{-1})				
AG3	260	52	517	171	Sandy clay loam
AG6	245	62	465	228	Sandy clay loam
PP	450	87	302	161	Clay
AS	358	72	343	227	Clay
IC	250	58	521	171	Sandy clay loam
NV	255	72	583	90	Sandy clay loam

according to Embrapa's Manual of Methods of Soil Analysis (Donagema et al. 2011).

Equilibrium humidity data were obtained with the potentials corresponding to -10, -60, -100, -330, -3000, -10.000, and -15.198.75 hPa, using the centrifuge method (Reatto et al. 2008). At the end of water desorption process, the soil density (Ds, in g cm^{-3}) was measured by the volumetric ring method, with dry soil mass obtained in the oven at 105 °C. For each humidity value (W), the relative humidity (Wrel) was calculated using the formula: Wrel = (W - W15.198,75 hPa)/(Ws - W15,198.75 hPa), where W in (g g^{-1}) whereby the gravimetric humidity corresponding to each voltage; Ws (in g g^{-1}) is the gravimetric humidity measured at saturation, determined by direct weighing of the saturated soil sample; W15.198.75 hPa (in g g^{-1}) is the gravimetric humidity corresponding to the potential of -15,198.75 hPa; and the difference Ws - W15.198.75 hPa is the effective saturation (We, in g g^{-1}) of water in the soil (Santos et al. 2011). The readily available water (Wra, in g g^{-1}) was calculated by the formula: Wra = W60 hPa - W10,000 hPa.

The macroporosity (Ma, in g g^{-1}) was calculated by difference between the total soil porosity (Pt, in g g^{-1}) (Silva & Azevedo 2001) and the respective humidity in equilibrium with the potential of -60 hPa, according to the formula: Ma = Pt - W60 hPa, where W60 is the gravimetric humidity measured at the potential of -60 hPa, and Pt is the total porosity (g g^{-1}). The potential of -60 hPa was considered as the reference limit between macroporosity and microporosity (Mi, in g g^{-1}), obtained in each WRC (Santos et al. 2011).

The total soil porosity (Pt, in g g^{-1}) or total pore volume was calculated using the formula: Pt = 1/Ds - 1/Dp, where Ds is the soil density (g cm^{-3}) and Dp is the soil particle density (g cm^{-3}). The determination of the unsaturated pores (Pu) was obtained using the formula: Pu = Pt - Ws and blocked pores by the formula: Pb = Pt - Ptd, where Pt is the calculated porosity (g g^{-1}) and Ptd is the porosity total (Ptd = Ws * Ds, in g g^{-1}). The void index "E" was calculated using the formula: E = Pt/(1 - Pt), (dimensionless).

The determination of penetration resistance (RP) was done with a 4 kg impact penetrometer (standard). The transformation of the penetration of the rod of the apparatus into the soil (in impact^{-1}), in resistance to penetration, was obtained through of the expression of "Dutch", simplified by Stolf (1991), according to Equation 1.

$$RP=\frac{Mg+mg+\left[\frac{M}{M+m}*\left(\frac{Mg*h}{x}\right)\right]}{A} \tag{1}$$

where: RP - resistance to penetration, kgf cm^{-2}; M plunger mass (4 kg) (Mg = 4 kgf); m - mass of the apparatus without plunger (3.2 kg) (mg = 3.2 kgf); h - plunger drop height (40 cm); x - penetration

Table II. History of areas under crop, in Southwestern Piauí.

Areas	Description
AG3	Opening of an area carried out in 2008 and conducted under conventional tillage and crop of Andropogon grass (*Andropogon gayanus*), grazed with goats. Area with three years of use under pasture.
AG6	Opening of an area realized in 2005 and conducted under conventional tillage and crop of Andropogon grass (*Andropogon gayanus*), grazed with goats. Area with six years of use under pasture.
PP	Opening of an area held in 2005 and conducted under conventional tillage and irrigated maize (Zea mays) crop. In the 2006/2007 crop, conventional tillage and irrigated tomato crop. In the years 2007 to 2009, crop of unripe napier grass (*Pennisetum purpureum*). In the years 2010 to 2011, crop of napier grass with cut twice a year, irrigated by sprinkling.
AS	Opening of an area held in 2006 and conducted under conventional tillage and orchard crop (*Annona squamosa* L.). Area with five years of use with culture.
IC	Opening of an area realized in 2007 and conducted under intensive conventional tillage and cowpea (*Vigna unguiculata*) irrigated under pivot. In the 2008/2009 harvest, conventional tillage and maize (*Zea mays*) irrigation under pivot. In the 2009/2010 crop, conventional tillage and irrigated cowpea under pivot and in the 2010/2011 crop, conventional tillage and irrigated maize under pivot. Area with four years of intensive crop. In maize crop, in all crops, the plants were harvested for ensiling.
NV	Native vegetation of cerrado/caatinga ecotone.

of the rod of the apparatus, in impact^{-1}, and A - cone area, 1.29 cm^2.

The values of RP were multiplied by the factor 0.098 to obtain RP in MPa. Measurements were performed randomly, at six points around the trenches, six readings were taken to obtain an average value per point, totalling 18 repetitions per area, as described by Marchão et al. (2007). RP was measured concomitantly with soil humidity in each of the five cultivated areas and native vegetation.

The field saturated hydraulic conductivity (K_{sl}) was evaluated using the Guelph permeameter (Reynolds & Elrick 1987) from soil holes 0-0.10 meters deep, with a radius (R) of 3 cm, and hydraulic load (H) of 3 or 5 cm, which depended on velocity of infiltration of water into the soil. Six measurements were made at the same points where the trenches were opened, totaling 18 replicates per area. The K_{sl} values were obtained by the formula: K_{sl} = CQ/(2πH2+CπR2+2πH/A), from Reynolds & Elrick (1987), where, K_{sl} is the saturated field hydraulic conductivity (cm s^{-1}); Q is the average flow infiltration in the soil (m^3 s^{-1}); H is the hydraulic load (cm); R is the radius of the hole (cm); A is the parameter associated with soil texture and structure (cm^{-1}); C is a dimensionless factor, established as a function of the H/R ratio.

For statistical analysis, the assumptions of additivity and independence of errors by graphical analysis, the homogeneity of the variances by the Bartlett test and the normality of errors by Shapiro-Wilk test were investigated. In order to compare the results of the physical-water attributes in the different systems of use, the Scott-Knott test was used at 5% of significance ($p < 0.05$) using the Sisvar program (Ferreira 2014). To verify whether soil humidity and density are related in any way, a second degree polynomial regression analysis was performed at 1% significance. We considered the averages of three repetitions at depth 0-0.10 meters in all areas, formed in Microsoft Excel 2010 by six rows (areas) and two columns (variables). For application of multivariate analysis, the Bartlett sphericity test ($p < 0.05$) was performed, followed by the Kaiser Meyer Olkin test (KMO). The relationship between the soil physical attributes and centroids of confidence ellipses for each area was verified through the statistical program XLSTAT® 2016 (Addinsoft 2016), a Microsoft Excel 2010 plug-in.

RESULTS AND DISCUSSION

Soil physical-hydric attributes

The physical-hydric attributes were affected by soil use systems (Table III). The systems that showed more pronounced positive changes were AG6 and AS, and AG6 presented the best set of positive effects, with lower values of Ds and Mi and higher values of Pt, Ma, Ws, We, Wra and E, even surpassing NV. On the contrary, the PP system showed the highest values of Mi and the lowest values of Pt, Ma, Pu, Pb, We, Wra and E, when compared to NV.

The highest values of Ds were observed in IC, NV and PP systems and the lowest value in AG6. In this sense, the lower value of Ds in AG6 may be related to the longer time of forage crop (Table II) and at the same time, contributing to a more abundant development of the root system of this grass, thus improving soil structural conditions, consequently, collaborating in the value of Ds determined in this area of crop. Pragana et al. (2012) studying the physical quality of Latossolo Amarelo in Piauí State observed a significant effect of the management systems on the Ds, and native cerrado presented the lowest value of this attribute in the superficial layer, compared to cultivated soils, that did not differ statistically among them, evidencing that the different management times did not contribute to improve the Ds altered by the years of anthropization of the cultivated areas.

In the present study, although significant changes were observed in Ds values between the evaluated systems, including NV, the values found in AG3, AG6, IC and NV were considered

Table III. Physical-hydric attributes under different crops, in Southwest of Piauí.

Treatments [2]	**Physical-hydric attributes**[1]									
	Ds	**Pt**	**Ma**	**Mi**	**Pu**	**Pb**	**Ws**	**We**	**Wra**	**E**
	(g cm^{-3})	**(g g^{-1})**								**-**
AG3	1.49b	0.43b	0.28b	0.15c	0.15c	0.01c	0.28a	0.19a	0.06b	0.74b
AG6	1.46c	0.45a	0.30a	0.15c	0.17b	0.04a	0.28a	0.19a	0.07a	0.81a
PP	1.52a	0.40c	0.21d	0.19a	0.13d	0.00d	0.27b	0.14c	0.04c	0.67c
AS	1.49b	0.45a	0.26c	0.19a	0.16b	0.03b	0.28a	0.16b	0.06b	0.81a
IC	1.53a	0.43b	0.26c	0.17b	0.17b	0.03b	0.26b	0.16b	0.06b	0.76b
NV	1.52a	0.45a	0.28b	0.17b	0.19a	0.05a	0.27b	0.16b	0.06b	0.80a
Mean	1.50	0.43	0.27	0.17	0.16	0.03	0.27	0.17	0.06	0.77
CV (%)	2.10	2.77	4.98	4.15	5.64	52.74	4.72	9.52	9.53	4.56
Standard error (±)	0.009	0.003	0.004	0.002	0.003	0.004	0.004	0.005	0.002	0.01

[1]Soil density (Ds); total porosity (Pt); macroporosity (Ma); microporosity (Mi); unsaturated pores (Pu); blocked pores (Pb); saturation humidity (Ws); effective saturation (We); water readily available (Wra); soil void index (E). Three-year-old andropogon grass (AG3), six-year-old andropogon grass (AG6), napier grass (PP), ata orchard of *Annona squamosa* L. (AS), pivot with intensive crop of cowpea and irrigated maize with central pivot (IC) and native vegetation (NV), coeficiente of variation (CV). Different lowercase letters in the same column indicate differences by the Scott-Knott test at 5% significance ($p < 0.05$).

lower than the critical index established for root growth in sandy loam (Table I) by Israelsen; Hansen (1965) and Arshad et al. (1996) (upper limit of Ds = 1.80 and 1.60 g cm^{-3}, respectively). In the opposite way, for PP, Ds values for clayey soils were considered at the upper critical limit established by Cavenage et al. (1999), Silva et al. (2006) (upper limit of Ds = 1.53 g cm^{-3}), for the growth and adequate development of the roots of cultivated species.

The Pt in the AG6, AS and NV systems were higher, while the PP system showed the lowest values. For Ma, the AG6 system was the one that had the greatest expressiveness and PP the lowest expressiveness. For PP, lower values of Pt and Ma may be associated with higher values of Ds and Mi in this crop, resulting in increased soil penetration resistance. Higher values of soil density and negative change in soil compaction were verified by Silva et al. (2017) attributed to animal herding and decline of vegetation cover, reducing soil protection against direct impacts over the years of cultivation, since this area has a longer use time than other areas.

According to Andrade & Stone (2009), the lower limit of macroporosity is around 0.10 g g^{-1} and was recommended by Kopecky (1927) as the minimum necessary for the satisfactory growth and development of root systems. According to Hatano et al. (1988), there is a close relationship between soil porosity and root growth. In general, aeration porosity values below 0.10-0.15 g g^{-1} are almost always considered restrictive for growth and productivity of most crops, despite the dependence of the plant species on biological activity of the soil and soil humidity regime (Watanabe et al. 2002, Andrade & Stone 2009). However, all the cultivated areas and soil layers evaluated presented values of the macroporosity/total pore volume (Ma/Pt) lower than 0.33 g g^{-1}, which is considered to be ideal for plant development of according to Torres et al. (2011), Rosset et al. (2014).

It is also worth noting that the lower values of Mi in the present study are associated with higher values of Ws and We in the AG3 and AG6 systems, respectively, because these use and management systems have preserved the highest Pt values, allowing full pore filling by water, still observed in AG6 expressive values of Wra and E. Thus, the management conditions for these pastures suggest that they are only partially affected by negative form. According to Balbino et al. (2001), when inadequate pasture management is obtained, a reduction in total soil porosity affecting the available water reserve is observed as soil microporosity decreases. As for the set of attributes related to the soil water content (Ws, We), the values found in the AG6 and AG3 systems were similar to each other, but higher than the other systems, including NV.

Regarding the physical-hydric quality of the studied systems, “E” (E = 0.81) is represented in AG6 and AS as those of better physical-hydric quality, to the detriment of PP system in which “E“ (E = 0.67) differed negatively from all other systems, confirming the negative effect of the same on representative attributes of porosity and soil water storage. According to Silva et al. (2017), the reduction of soil void index is a consequence of the increase on Ds, due to greater packing of particles caused mainly by the frequent use of agricultural machinery and equipment. This reduction in the voids content may cause a reduction in the soil hydraulic conductivity and compromise the soil physical-hydric quality. Schossler et al. (2018) verified a reduction of the physical-hydric quality in soils of the region after having submitted to agricultural production systems when compared to the native vegetation.

In general, the greatest negative order changes were observed in the 0.10-0.20 and

0.20-0.30 m depths layers, respectively, due to the effect of the plow, while the 0-0.10 m layer (less altered than earlier), possibly is attributed to higher soil organic matter contents that remain conserving certain physical-water properties, forming the stability of soil structure (Rawls et al. 1991). The 0.40-0.50 m depth layer showed smaller changes than all previous layers, as it is farther from the reach of agricultural implements (Table IV). These results show those the intermediate layers were more influenced by anthropogenic changes resulting from the use of agricultural implements (layers ranging from 0.10-0.30 m deep), mainly due to the action of the plow cutting disc and / or plow harrow. reducing the quality of the physical-water attributes.

Regarding the attributes Ds and Pt in the 0-0.10 m depth layer, possibly the main differences observed can be attributed to the greater movement of agricultural machinery and implements on the soil surface. In studies conducted by Marchão et al. (2007), Santos et al. (2011) and Silva et al. (2017) attributed the greatest negative order changes in the physical-water attributes (such as: Ds, Pt, Ma, Mi, Mie, Ws, We, Wra, RP and K_{sl}) in the topsoil mainly by trafficability of machinery and equipment and animal trampling more frequently. For the layers up to 0.30 m deep, these authors attributed the negative order changes for the same physical-hydraulic attributes, the residual effect left by the action of plow disk or grid used initially or with some frequency in the preparation of the soil, causing a compaction in the subsurface portion of the layers of “foot-of-grid” soil that can persist for several cycles of crop in these areas.

As regards the distribution of Ds values in the different soil layers (Figure 1a), higher values were observed in PP, IC and NV systems and the lowest values in AG6, AG3 and AS for the superficial layer of 0-0, 10 m deep. In the 0.10-0.20 m depth layer (Figure 1b), the most pronounced value of Ds was found in the IC system, while the lowest value was in AG6. Even higher scores (Ds = 1.78 g cm^{-3}) than those presented in IC of this study were found by Sales et al. (2016), indicating that the greater compaction in the same layer of Latossolo Vermelho-Amarelo (Oxisol), with a sandy clay loam texture under sunflower crop was related to the intensive use of agricultural implements in the conventional preparation of the soil.

In the 0.20-0.30 m depth layer (Figure 1c), PP system defined the highest Ds measured, whereas the AG6, IC, AG3 and NV systems showed reduced values of this attribute. Finally,

Table IV. Physical-hydric attributes in different soil layers in South-western Piauí.

Layers (m)	Physical-hydric attributes[1]									
	Sd ---------	Pt	Ma	Mi	Pu	Pb	Ws	We	Wra	E -------
	(g cm^{-3})	(g g^{-1})								
0-0.10	1.50b	0.43b	0.27a	0.16c	0.16a	0.03a	0.27b	0.17b	0.06a	0.77b
0.10-0.20	1.55a	0.42c	0.26b	0.15d	0.16a	0.03a	0.25c	0.15c	0.05b	0.71c
0.20-0.30	1.53a	0.42c	0.25b	0.17b	0.16a	0.03a	0.26c	0.15c	0.05b	0.74c
0.40-0.50	1.43c	0.46a	0.28a	0.18a	0.15b	0.02a	0.31a	0.19a	0.06a	0.85a

[1] Soil density (Sd); total porosity (Pt); macroporosity (Ma); microporosity (Mi); unsaturated pores (Pu); blocked pores (Pb); saturation humidity (Ws); effective saturation (We); water readily available (Wra); soil void index (E). Different lowercase letters in the same column indicate differences by the Scott-Knott test at 5% significance ($p < 0.05$).

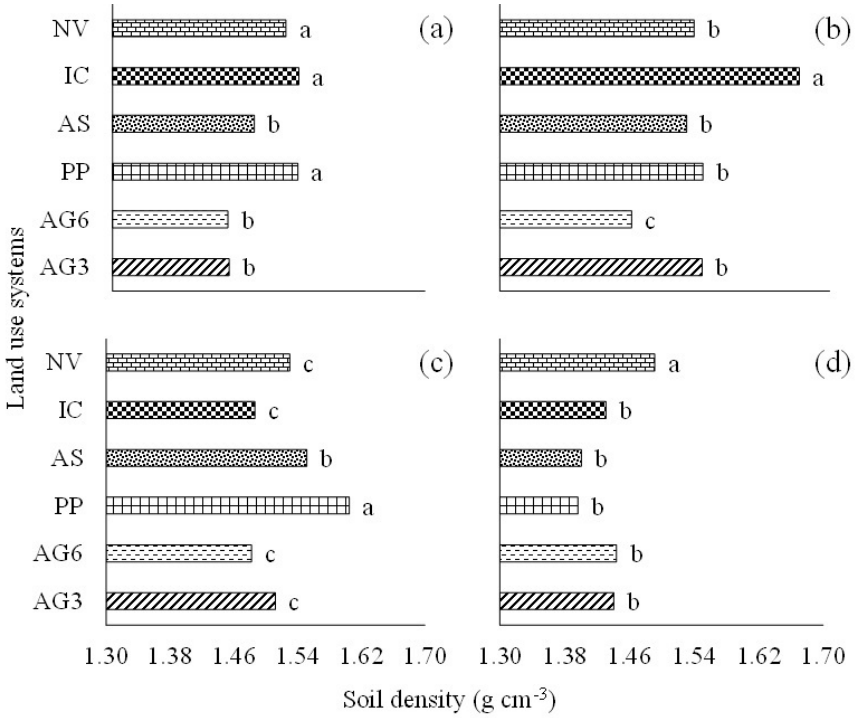

Figure 1. **Soil density as a function of the systems of use in the Southwest of Piauí. Andropogom grass with six years of use (AG6), napier grass (PP), ata orchard of *Annona squamosa* L. (AS), pivot with intensive crop of cowpea and irrigated corn with central pivot (IC) and native vegetation (NV), in Southwestern Piauí.**

in the 0.40-0.50 m depth layer (Figure 1d), the NV area, in relation to all others, was the one with the highest values of Ds. Fontana et al. (2016) observed values of more than 1.64 g cm^{-3} in the 0.10-0.26 m depth layer in the Latossolo Vermelho Amarelo of medium texture cultivated with soybean and attributed these results to the association between compaction caused by the negative effect of anthropization and a pedogenic densification that can occur in this type of soil. Therefore, the use of agricultural implements for soil preparation, even for short term, promotes an increase in the values of Ds that can be negatively reflected to the growth of the plants for long periods, even after the mechanical preparation of the soil has ceased.

When the relation between humidity and Ds (Figure 2) is made in the different soil layers, it is observed that there was a negative correlation between these attributes, that is to say, to the extent that there is a reduction of soil humidity, a polynomial increase of Ds in all layers, with coefficients of determination above 81%. Also, it can be observed that the lowest values of soil humidity were observed in the 0.10-0.20 m depth layer (Figure 2a), associated with the highest values of Ds. In contrast, the 0.40-0.50 m depth layer (Figure 2d) was the one that retained the highest soil humidity, showing the lowest values of Ds.

In this sense, Silva et al. (2017) studying the impact caused by different systems of use and management on the physical and hydraulic attributes of Latossolo Amarelo in the Southwest of Piauí, observed that from the value of Ds ≥ 1.43 g cm^{-3}, soil water availability was heavily reduced in different areas of crop. Likewise, Dias et al. (2016) also observed a negative linear reduction of soil water content in the same proportion as the values of Ds under different types of management, also affirming that this result is typical of soils compacted.

Soil resistance to penetration (RP)

In relation to RP, it is observed that it differs in different cropping systems and the native

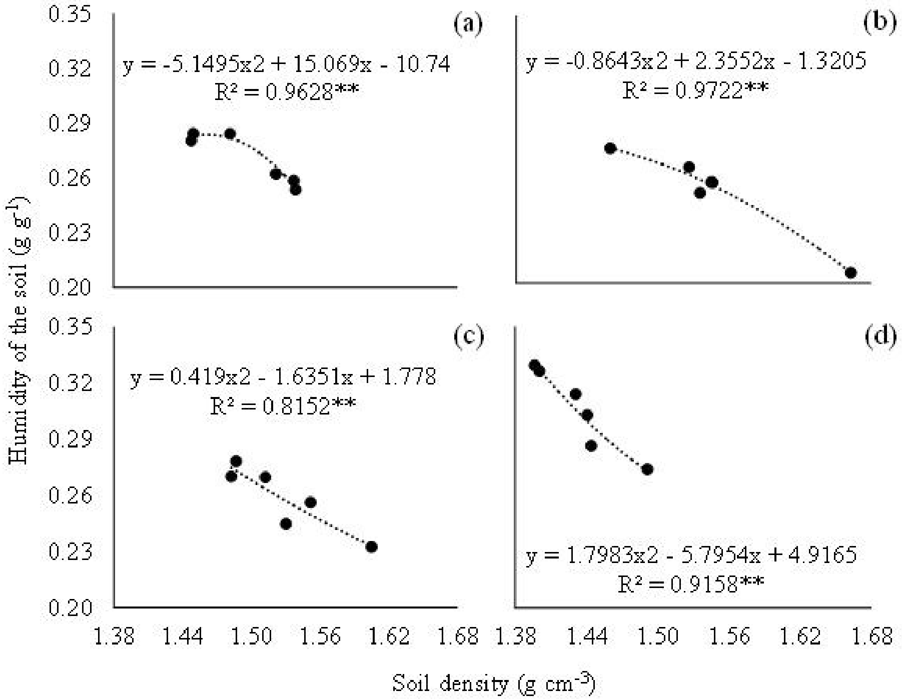

Figure 2. Correlation between the values of soil humidity and density in the layers 0-0.10m (a), 0.10-0.20 m (b), 0.20-0.30 m (c) and 0.40-0.50 m (d) depth, obtained in Cerrado/Caatinga ecotone, in the Southwest of Piauí. ** Significant at 1% significance by the F test ($p < 0.01$).

vegetation area, as well as there is also change in soil humidity (Figure 3). The AS crop presented the highest RP in the 0.2-0.3 m depth layer. This plant species has a deep pivoting root, however, most of its root system is superficial and branched (Gardiazábal & Rosemberg 1988) and may have significantly interfered with higher RP values in this crop. Already, the area with the second highest RP, possibly due to frequent animal trampling of sheep and goats, causing soil compaction.

In general, the layers with the highest RP values for most cultures were 0.1-0.2 and 0.2-0.3 m deep. The RP values observed in the 0.10-0.20 m depth layer corroborate the explanation of the lower humidity values and higher Ds values observed in this same soil layer (Figure 2). The increase of RP with the increase of Ds values is related to the effect of soil compaction, which according to Vepraskas (1984), results in a greater contact or friction between soil particles.

Saturated hydraulic field conductivity (K_{SL})

For hydraulic conductivity (K_{sl}) (Figure 4) it was observed that the highest values occurred in the NV, AS, PP and AG3 systems in the 0-0.10 m deep layer, respectively, while the lowest values were observed in the IC and AG6 systems. Probably, the lowest values of K_{sl} observed IC are related to the intensive and irrigated crop under pivot (Table II) during four years, since the observed K_{sl} low must be associated to conventional tillage with use of plow twice a year, intense traffic machines for planting, cultivating and maize silage. All these operations with machines and equipment can negatively affect the soil structure, mainly interfer with the reorganization of soil porous system in order to contribute to reduction of water and air distribution in the soil profile (Marsili et al. 1998).

However, the lowest value of K_{sl} observed in AG6 is not associated with the attributes Ds, Pt and Ma (Table III), but rather with Pb values (0.04 g g^{-1}) that can reduce K_{sl} values. The results

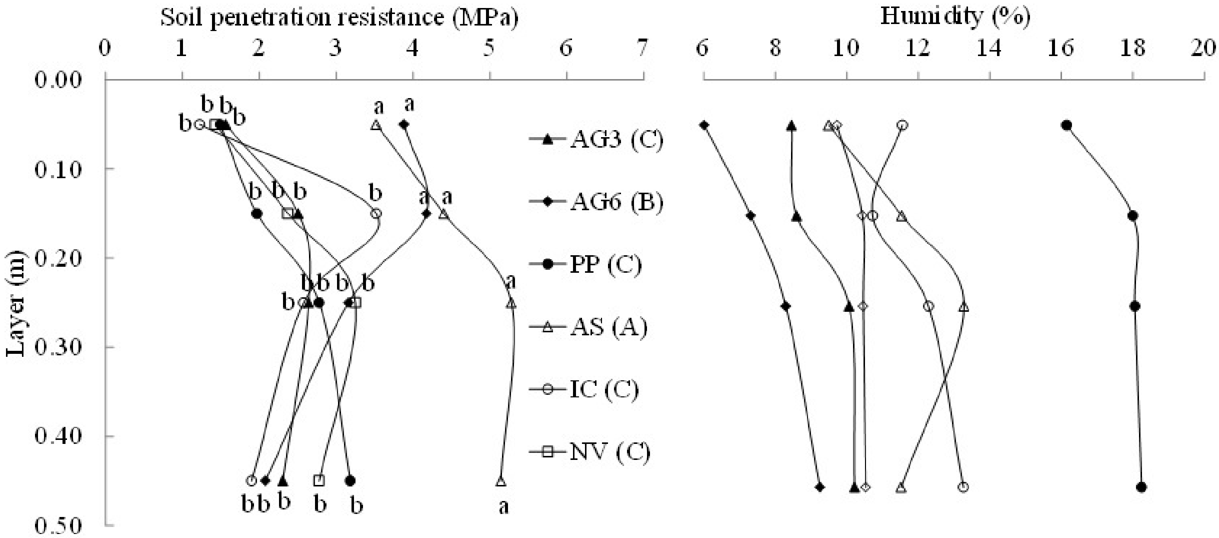

Figure 3. Values of soil resistance to penetration and humidity profile in the layers 0-0.10, 0.10-0.20, 0.20-0.30 and 0.40-0.50 m depth under systems of use in Southwest Piauí. Andropogom grass with six years of use (AG6), napier grass (PP), ata orchard of *Annona squamosa* L. (AS), pivot with intensive crop of cowpea and irrigated corn with central pivot (IC) and native vegetation (NV). Different lowercase letters in columns and different capital letters in parentheses in columns indicate statistical difference by Scott-Knott's mean test at 5% significance (p <0.05).

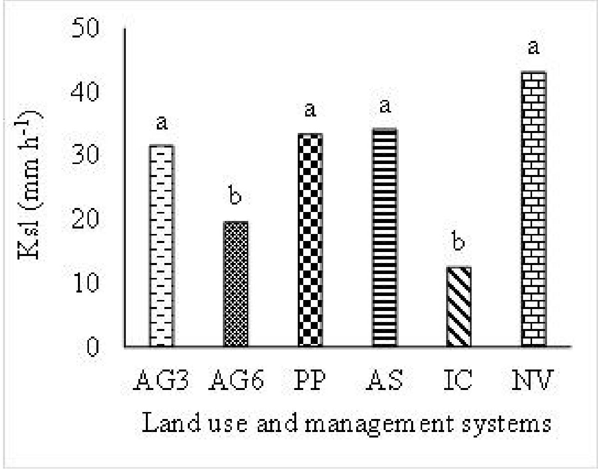

Figure 4. Values of field saturated hydraulic conductivity (Ksl) in the 0-0.10 m deep layer under systems of use, in Southwest of Piauí. Different lowercase letters indicate statistical difference by the Scott-Knott mean test at 5% significance (p <0.05). Andropogom grass with six years of use (AG6), napier grass (PP), ata orchard of *Annona squamosa* L. (AS), pivot with intensive crop of cowpea and irrigated corn with central pivot (IC) and native vegetation (NV). Different lowercase letters in columns and different capital letters in parentheses in columns indicate statistical difference by Scott-Knott's mean test at 5% significance (p <0.05).

of this study indicate a direct relationship with animal trampling, both for cattle and for goats that forage the area (Albuquerque et al. 2001, Santos et al. 2011), increasing soil compaction and soil disintegration in this layer corroborating with results obtained by Figueiredo et al. (2009). Thus, the soil structure that has been negatively altered by animal trampling in smaller particles (fractions of the soil size distribution) may, over time, be transported by the lateral and vertical movement of water inside the soil, raising the quantitative of Pb, interfering negatively with the K_{sl} of the soil.

Analysis of main components of physical-hydrical attributes, soil resistance to penetration and saturated field hydraulic conductivity

The relationships between the physical-water attributes are explained in the principal component analysis (PCA) (Figure 5). The variability of data was explained in 42.05% in axis 1 and 22.15% in axis 2, totalling 64.20% of

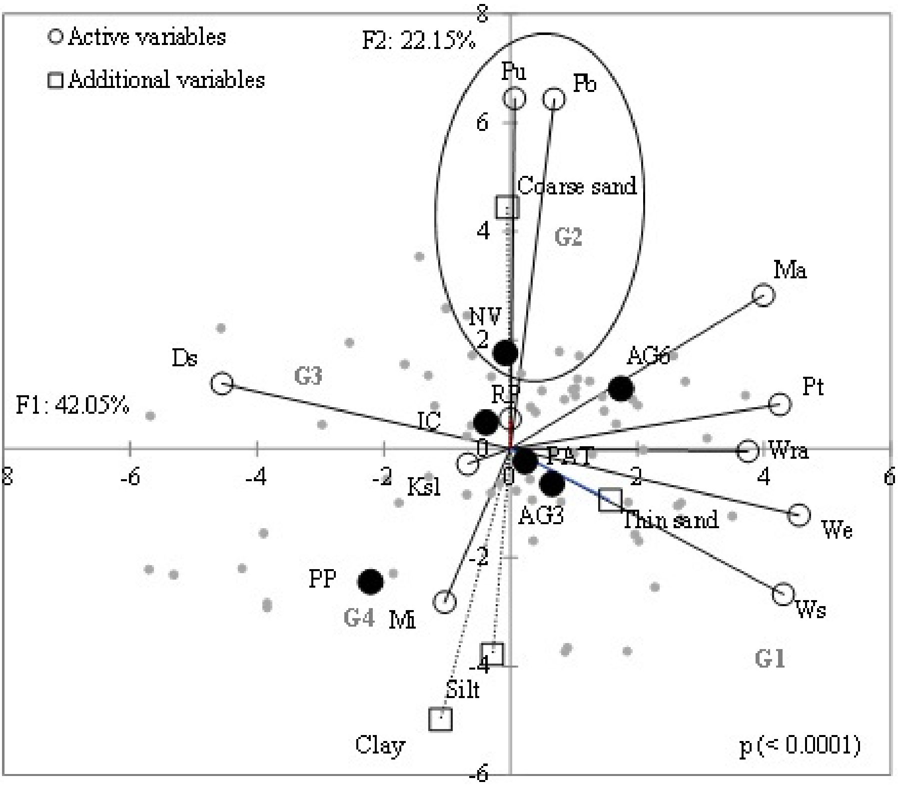

Figure 5. Principal components analysis (PCA) of the physical-water attributes under different land use systems in the Southwest of Piauí. Andropogom grass with six years of use (AG6), napier grass (PP), ata orchard of *Annona squamosa* L. (AS), pivot with intensive crop of cowpea and irrigated corn with central pivot (IC) and native vegetation (NV). Field saturated hydraulic conductivity (Ksl); microposition (Mi); soil density (Sd); macroporosity (Ma); total porosity (Pt); readily available water (Wra); effective saturation (We) and gravimetric humidity measured at saturation (Ws). Significant at 0.01% significance by the Bartlett test (p<0.0001).

total variability of the data. Axis 1 was influenced mainly by We attributes with factorial load of 0.93, Ws (0.88), Pt (0.87), Ma (0.819) and Wra (0.76), with positive eigenvectors and Ds (-0.93) with negative eigenvector, giving results of the correlations between humidity and soil density shown in Figure 2. Axis 2 was influenced by Pu (0.95) and Pb (0.95) attributes with positive eigenvectors, presenting negative association with the additional clay attribute (0.74).

According to Figure 5, it is possible to observe the formation of four distinct groups, regarding the behavior of the physical-hydric attributes. Group G1 represents the association of AG6 system with the positive order changes in physical-hydric attributes Ma, Pt, Wra, We and Ws, confirming the data shown in Table III. Although the factorial load of the fine sand fraction is low, it can be indicated that this attribute is related to G1, since it is in the same quadrant arranged in the PCA, which may interfere with higher porosity and soil humidity. The G2 group represents the association of the NV system with the attributes Pu and Pb. Although positive relationships are observed in statistics, these attributes should not be explained by coarse sand content. The G3 group represents the association of the IC area with the negative order changes in the Ds and K_{sl} attributes, and the G4 group represents the association of the PP area with the Mi attribute, partly explained by clay and silt contents.

CONCLUSIONS

The physical-hydric attributes of Latossolo Amarelo Distrófico are influenced by different systems of soil use in cerrado/caatinga ecotone, in Southwest of Piauí region, mainly in soil layers varying from 0.10-0.30 m depth.

Soil density, total porosity, macroporosity, saturation humidity, effective saturation, readily available water and void index are the attributes that suffer the least negative effects from the system of use of andropogom grass with six years of use, while crop intensive for five consecutive years and the irrigated area under intensive pivot for four years, present the greatest negative impacts.

The soil resistance to penetration is higher in the 0.10-0.20 m layer and 0.20-0.30 m depth in ata orchard area (*Annona squamosa* L.) and pasture area of *Andropogom grass* with six years of use, when compared the same depths of the same crops, evidenced root system and negative residual effect of the use of plow harrow in studied soil.

Irrigated and intensive crop under central pivot area influences negatively the saturated hydraulic conductivity in the 0-0.10 m depth layer of the Latossolo Amarelo Distrófico in a Cerrado/Caatinga ecotone region.

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DJAVAN P. SANTOS[1]
https://orcid.org/0000-0002-1811-5362

THIAGO R. SCHOSSLER[2]
https://orcid.org/0000-0002-5610-0065

ISIS L. DOS SANTOS[3]
https://orcid.org/0000-0002-4574-966X

NATHÁLIA B. MELO[1]
https://orcid.org/0000-0002-6603-0953

JÚLIO CÉSAR A. NÓBREGA[4]
https://orcid.org/0000-0002-2726-8205

GLENIO G. SANTOS[1]
https://orcid.org/0000-0002-0271-9751

[1]Programa de Pós-Graduação em Agronomia: Solo e Água (PPGA), Escola de Agronomia, Universidade Federal de Goiás (UFG), Campus Samambaia, Rodovia Goiânia-Nova Veneza, Km 0, 74690-900 Goiânia, GO, Brazil

[2]Programa de Pós-Graduação em Agronomia (Ciência do Solo), Universidade Federal Rural de Pernambuco (UFRPE), Rua Dom Manuel de Medeiros, s/n, Dois Irmãos, 52171-900 Recife, PE, Brazil

[3]Universidade de Brasília (UnB), Faculdade de Agronomia e Medicina Veterinária, Campus Darcy Ribeiro, ICC Sul, Asa Norte, s/n, 70910-900 Brasília, DF, Brazil

[4]Universidade Federal do Recôncavo da Bahia, Centro de Ciências Agrárias, Ambientais e Biológicas, Departamento de Engenharia Agrícola, Rua Rui Barbosa, 710, Prédio de Solos, Centro, 44380-000 Cruz das Almas, BA, Brazil

Correspondence to: **Djavan Pinheiro Santos**
E-mail: djavansantos@hotmail.com.br

Author contributions

Djavan Pinheiro Santos: conception, design, acquisition, analysis, interpretation of data and elaboration of the work. Thiago Rodrigo Schossler, Isis Lima dos Santos and Nathália Batista Melo: acquisition, analysis and substantial work review. Júlio César Azevedo Nóbrega and Glenio Guimarães Santos: conception, design, acquisition, analysis, interpretation of data and substantial work review. All authors reviewed and agreed with the submission of the work.