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Physical-hydric quality of a Regosols under integrated and conventional crop production systems

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Abstract

Sandy soils have gained increased attention due to the expansion of new agricultural frontiers in Brazil and worldwide, however, they are sensitive to land use changes. The objective was to evaluate the physical-hydric quality of a Regosols under integrated and conventional production systems in the climatic conditions of the semiarid domain of Paraíba, Brazil. The study was carried out in the municipality of Lagoa Seca/PB, Brazil (7°10'15" S, 53°51'43" W, and 640 m of altitude), on a Regosols with a sandy loam textural classification. The experiment was set up in an entirely randomized design, with five treatments and five repetitions. The treatments were composed of: 1) Mombaça grass (*Panicum maximum* Jacq.) + Maize (*Zea mays* L.) (M+M); 2) *Urochloa decumbens* (Stapf) R. D. Webster + Maize (U+M); 3) secondary forest (SF); 4) conventional agriculture area, cultivated with bean (*Phaseolus vulgaris* L.) (AGR); and, 5) area in regeneration stage (ARS). The following variables were analyzed: flocculation degree, clay dispersed in water, soil porosity (total, macroporosity, microporosity), aeration porosity in the macro pore domain, soil bulk density, hydraulic conductivity, and available water. According to the results, the physical-hydric quality of the soil between the integrated systems was not significant, but compared to the conventional system, it showed satisfactory results. On the other hand, it is concluded that the modification of soil structure in an agricultural area has reduced water availability to plants to 75.20% below what is considered adequate. Long-term studies should be conducted in order to verify the effect of integration systems on improving the physical and structural quality of sandy soils.

Key words: Available water; Conservationist agriculture; Semiarid; Sandy soil.

Introduction

Soil quality refers to the ability of a given class of soil to function, within the limits of natural or managed ecosystems, to sustain the productivity of plants and animals, maintain or improve water and air quality, and support human health and housing (KARLEN et al., 1997; SIMON et al., 2022). Among the attributes used to evaluate the quality of the soil, the structure has been one of the most studied, because it influences directly or indirectly the different processes that occur in the soil, such as water retention and infiltration, susceptibility to erosion, aeration, microbial activity, among others (RESENDE et al., 2012).

Sandy soils, despite having high water, gas, and heat infiltration (HUANG; HARTEMINK, 2021), are more susceptible to degradation because they lack a well-defined structure and poor horizontality (BRUAND et al., 2015), and are easily modified by crop management and biological disturbance (HUANG; HERTEMINK, 2021). In Brazil, the area occupied by sandy soils is 683,200 km^2 and are especially expressive in the Matopiba and Mato Grosso region (DONAGEMMA et al., 2016), where they are widely used in the production of maize (SPERATTI et al., 2017), and cotton (ANGHINONI et al., 2019), besides being present in areas of Tocantins, Minas Gerais, Goiás, Pará, Paraná, Rio Grande do Sul, São Paulo, and Mato Grosso do Sul (FONTANA et al., 2021). These soils comprise Arenosols, Regosols, and Leptosols, in addition to some Planosols, Gleysols, Podzols, Oxisols, and Acrisols (WRB-FAO, 2014).

In recent years, interest in sandy soils has gained prominence because they are easily managed and occur preferentially in regions with favorable relief for mechanization (FONTANA et al., 2021). For Lu and Tian (2017), this interest correlates positively with the increased use of fertilizers and irrigation for food production. However, despite recent advances related to the sustainable management of sandy soils (HUANG; HARTEMINK, 2021), the intensification of agricultural production seems to stall due to physical, chemical, and biological limitations, such as high susceptibility to compaction, low water retention and availability, low natural fertility, and inexpressible resilience (RAMALHO FILHO; BEEK, 1995). The implementation of conservationist production systems emerges as an alternative to minimize edaphic limitations, especially when these contribute considerable organic matter content (VEZZANI; MIELNICZUK, 2011; SENA et al., 2017). Aranyos et al. (2017) observed, for example, that organic matter input into sandy soil improved physical quality with substantial improvement in soil water infiltration rate, reduction in erosion, compaction level, and increase in permeability.

The integrated agricultural production systems are conservationist production systems that integrate the livestock and forestry components in rotation, consortium or succession, within the same production area, and have as a premise the intensive use of soil with minimal impact on ecosystem functions (BALBINO et al., 2011; VALANI et al., 2020). Studies have proven the effectiveness of integrated agricultural production systems in improving soil physical quality (VALANI et al., 2020; SILVA et al., 2021). Some benefits reported by studies are: greater contribution of organic matter and nutrient cycling (CONTE et al., 2011), reduced density and degree of soil compaction, increased porosity and aggregation (PEZARICO et al., 2013). In soils under integrated crop production systems, there was seasonality of nitrogen and organic carbon concentrations, decreasing the contents during the cultivation phase and recovering rapidly during the perennial phase (GALINDO et al., 2020; MAIA et al., 2021) when compared to conventional systems. In Regosols, Silva et al. (2021) observed that the adoption of the crop-livestock-forest integration system considerably improved macroporosity, saturated hydraulic conductivity, and soil aeration. However, as highlighted by Galindo et al. (2020), this response will depend on the production arrangement adopted.

Thus, this study tests the hypothesis that the adoption of different arrangements with integrated agricultural production systems in sandy soil contributes to the improvement of physical quality compared to conventional management systems (agriculture) and disturbed areas (in recovery stage). Therefore, the objective was to evaluate the physical-water quality of a Regosol under integrated and conventional production systems in the climatic conditions of the semiarid domain of Paraíba, Brazil.

Material and methods

Characterization of the experimental area

The experiment was implemented in an experimental area of the Empresa Paraibana de Pesquisa, Extensão Rural e Regularização Fundiária (Empaer), in the municipality of Lagoa Seca/PB, Brazil (7°10’15” S, 35°51’43” W, and 640 m of altitude). According to Köppen classification, the predominant climate in the municipality is tropical hot and humid (As’), with the highest precipitation occurring between the months of April and June, with an annual average of 990 mm (SILVA et al., 2015). The average annual temperature is 26°C and relative air humidity 79% (OLIVEIRA et al., 2009). The relief is characterized as strongly undulated, covered by sub-deciduous forest. The soil of the experimental area was characterized as Regosols of textural classification sandy loam (SANTOS et al., 2018). The textural classification of the soil is presented in Table 1.

The area was occupied with pasture and, in 2014, an experiment with no-tillage system (NTS) was implemented in experimental plots in the form of terraces due to the smooth-wavy relief. The soil was corrected and the different species of grass were sown in the field. The grasses were desiccated and the corn was sown on the straw. Soil fertilization in the experimental area was performed in order to meet the nutritional needs of maize, applying 160 kg ha^{-1} of monoammonium phosphate fertilizer (MAP). Two applications of fertilizers were performed at the V5 and V8 maize stages, using 100 and 150 kg ha^{-1} of urea and 80 kg ha^{-1} of potassium chloride (ZONTA et al., 2016). Weeds were controlled by applying herbicides 30 days after maize emergence. In order not to interfere in the development of the grasses, the presence of at least three tillers was taken into account before applying the herbicides for weed control, and four to six true leaves for maize.

Experimental design

The experimental design used was an entirely randomized design (ERD), with five treatments and five repetitions. The repetitions were represented by the sample points in each treatment, i.e. five sample points per treatment. The treatments were composed of the following arrangements: 1) *Urochloa decumbens* (Stapf) R.D. Webster + Maize (*Zea mays* L.) (U+M); 2) Mombaça grass (*Panicum maximus* Jacq.) + Maize (M+M); 3) Secondary forest (SF); 4) Conventional agriculture area, cultivated

Table 1 – Textural classification of a Regosol under integrated and conventional crop production systems, Lagoa Seca/PB, Brazil.

Treatments	Sand	Silt	Clay	Textural Classification
		g kg^{-1}		
		0-10 cm		
M+M	800	88	112	Loamy Sand
U+M	850	88	62	Loamy Sand
SF	817	88	95	Loamy Sand
AGR	770	118	112	Sandy Loam
ARS	671	188	141	Sandy Loam
Average	782	114	104	Sandy Loam
CV (%)	8.4	35.1	47.1	
		10-20 cm		
M+M	785	97	118	Loamy Sand
U+M	840	87	73	Loamy Sand
SF	775	104	121	Sandy Loam
ARS	823	94	83	Sandy Loam
Average	624	127	249	Sandy Loam
CV (%)	8.4	35.1	47.1	

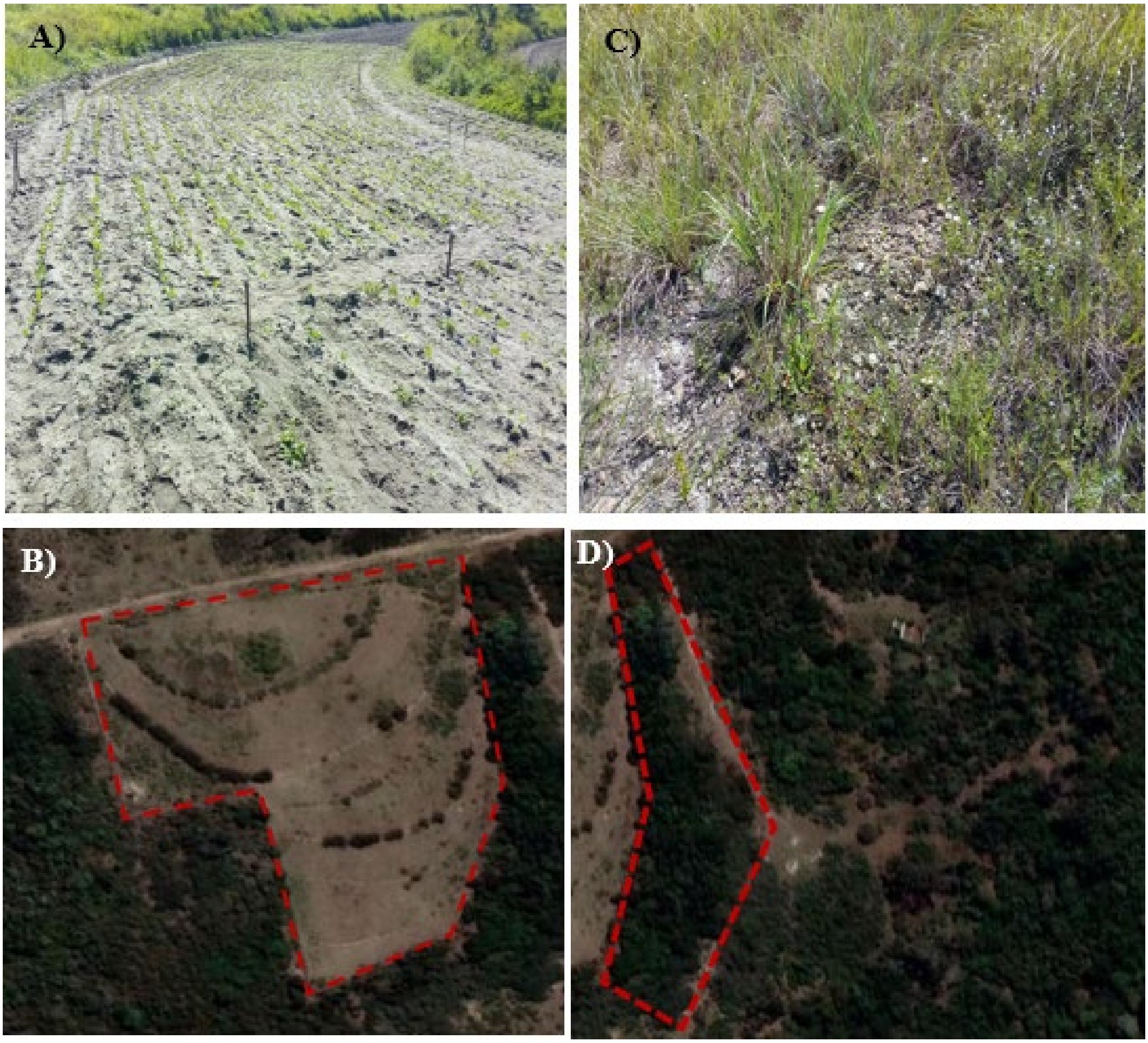
Legend: M+M – Mombaça grass + Maize; U+M – *Urochloa ruziziensis* (Stapf) R.D. Webster + Maize; SF – Secondary Forest; AGR – Conventional agriculture; ARS – Area in regeneration stage; CV – Coefficient of variation.

Source: Prepared by the authors (2022).

with bean (*Phaseolus vulgaris* L.) (AGR); and, 5) area in regeneration stage (ARS) (Figure 1). The SF treatment (3) was used as the reference treatment, as the area was found to be in a good state of conservation with no apparent human interference. The soil samples with deformed and undeformed structure (volumetric rings) were collected in two layers (0-10 and 10-20 cm depth), totaling ten samples per treatment. These were collected in the plots on a regular grid of 10 m distance between points, in order to represent the spatial variability of the soil attributes in the treatments.

The volumetric rings used in the collection of the undeformed samples had a volume of 98.17 cm^3, and for the deformed samples a cutting spade was used. It should be noted that the samples were collected after the corn harvest, with the grasses in full development. For the area in the regeneration stage, the surface layer of soil was removed from the construction area of an adjacent dam, chosen because it is

Figure 1 – Areas used as treatment in the evaluation of the physical-hydric quality of the Regosol, Lagoa Seca/PB, Brazil. A) Conventional agriculture area; B) Area with crop-livestock integration (CLI) composed of the treatments (1) *Urochloa decumbens* (Stapf) R.D. Webster + Maize and (2) Mombaça grass + Maize; C) Area in regeneration stage; D) Secondary Forest.



Source: A and C: The authors; B and D: Google Maps (2022).

located in the same soil class and because it is in the regeneration stage, with the colonization of some species of grasses and small shrubs.

Soil samples with deformed structure were sieved on 2.0 mm mesh and air dried (fine air dried soil - FADS). They were used in the granulometric characterization of the soil (sand, silt, and clay contents) by the densimeter method (GEE; BAUDER, 1986) and in the determination of clay dispersed in water (CDW) and degree of flocculation (DF) according to the methodology described by Teixeira et al. (2017). The sand fraction of the soil was separated into size classes using sieve sets with mesh sizes of 1.0, 0.50, 0.250, 0.105, and 0.053 mm. The samples with undeformed structure (volumetric rings) were saturated for 48 h and, subsequently, used in the determination of field capacity (θ_{FC}, $m^3\ m^{-3}$) and permanent wilting point (θ_{PWP}, $m^3\ m^{-3}$). For the determination of θ_{FC}, the samples were placed on a tension table to drain until hydraulic shear was reached, applying the potential of -100 hPa (BALL; HUNTER, 1988) and -15,000 hPa for θ_{PWP} using Richard's extractor with porous plates (KLUTE, 1985). The available water (θ_{AW}, $m^3\ m^{-3}$) was calculated using the ratio $\theta_{FC} - \theta_{PWP}$.

Total soil porosity (TP, $m^3\ m^{-3}$) was determined by taking the saturated soil water mass into account. To determine macroporosity (Mac, $m^3\ m^{-3}$) the water content retained at -60 hPa matrix potential was used on a tension table. Soil microporosity (Mic, $m^3\ m^{-3}$) was calculated by subtracting Mac from TP (TEIXEIRA et al., 2017). Soil porosity in the macro-pore domain (ApMac, $m^3\ m^{-3}$) was determined as described in Reynolds et al. (2002), using the following equation: ApMac = TP – 0.01.

To determine the saturated soil hydraulic conductivity (K_θ), a constant-load permeameter and previously saturated soil samples with an undeformed structure were used. The values of K_θ were obtained using Equation 1.

$$K_\theta = (Q \times L) \div (A \times H \times T) \qquad \text{Eq. 1}$$

Where K_θ is the saturated soil hydraulic conductivity (cm h^{-1}); Q is the volume of water collected in the measuring cylinder (percolate) (mL^{-1}); L is the height of the ground block (cm); A is the cross-sectional area of the cylinder (cm^2); H is the sum between L and the water column (cm); and, T is the time used in collecting the percolate in the beaker (h).

The means of the variables were analyzed by variance analysis (ANOVA) and, when significant, the Tukey test was applied ($p < 0.05$). The Mixed statistical procedure with pseudorandom replicates was used and all analyses were performed using the free software R (R DEVELOPMENT CORE TEAM, 2013).

Results and discussion

The average values of CDW and DF for the 0-10 and 10-20 cm depth layers are shown in Table 2. It can be seen that there was no significant difference ($p < 0.05$) for the response variables among the treatments evaluated; however, comparing between layers, in the 0-10 cm depth the average CDW was 20.10 g kg^{-1}, differing from the 37.78 g kg^{-1} found in the 10-20 cm depth layer.

At depth (10-20 cm), there was a 46.83% increase in CDW content, with a coefficient of variation of 51.90%. The treatments that impacted this result were: M+M, with 57.00 g kg^{-1}; U+M, with 43.33 g kg^{-1}; and SF, with 38.00 g kg^{-1}. The increase in CDW in the 10-20 cm depth layer results from the lower deposition of soil organic matter and the absence of hydrogen (H^+) and aluminum (Al^{+3}) cations in the soil solution, when compared to the 0-10 cm layer (SOUZA et al., 2005). Soil organic matter, as well as iron (Fe) and aluminum (Al) oxides and hydroxides, is considered a cementing agent for primary and secondary particles (BASTOS et al., 2005), and the soil wetting and drying cycles can also be included in this process (MALTONI, 1994). The DF is inversely proportional to the CDW content; thus, it can be seen in Table 2 that the highest DF values were found in the treatments with the

Table 2 – Clay dispersed in water and degree of flocculation of a Regosols under integrated and conventional production systems, Lagoa Seca/PB, Brazil.

Layer (cm)	Treatments	CDW	DF
		(g kg^{-1})	
0-10	M+M	17.00 a	857 a
	U+M	11.33 a	937 a
	SF	20.33 a	810 a
	AGR	25.41 a	847 a
	ARS	33.60 a	807 a
Average		20.10*	851
CV (%)		51.9	15
10-20	M+M	57.00 a	740 a
	U+M	43.33 a	900 a
	SF	38.00 a	770 a
	AGR	16.72 a	783 a
	ARS	33.89 a	853 a
Average		37.78	809
CV (%)		51.9	15

Legend: M+M – Mombaça grass + Maize; U+M – *Urochloa ruziziensis* (Stapf) R.D. Webster + Maize; SF – Secondary Forest; AGR – Conventional agriculture; ARS – Area in regeneration stage; CV – Coefficient of variation; CDW – Clay dispersed in water; DF – Degree of flocculation; * Significant ($p < 0.05$).

Source: Prepared by the authors (2022).

lowest CDW content. Comparing the average DF values between soil layers, there was a reduction of 42.00 g kg^{-1} in the 10-20 layer compared to the 0-10 cm layer, that is, an increase of 4.93% in the level of structural vulnerability of the soil.

Analyzing the average values for the different treatments presented in Table 2, it is possible to infer that in the soil layer with greater organic matter deposition and greater concentration of roots, there is a tendency to improve the structural stability of the soil, due to lower CDW values and higher DF values. For Albuquerque et al. (2005), the joint action between soil organic matter, microorganisms, root system, and the presence of exchangeable cations in the soil directly influence clay dispersion and soil DF. On the surface, one notices lower DF of the soil under regeneration area (807 g kg^{-1}), that is, 5.17% below the average value found for the 10-20 cm depth layer. For Lunardi Neto et al. (2008), the absence of vegetation cover is considered one of the factors that influence the greater dispersion of clay in areas that have been degraded and are in the process of regeneration. As in these areas the impact directly modified the soil macrostructure, one of the consequences is the abrupt increase in the CDW content (PRADO; CENTURION, 2001).

As observed by Figueiredo et al. (2021), the DF and the CDW are directly affected by the management system and by the soil electrochemical balance; that is, in disturbed soils, with accentuated modification of the structure, there is a tendency to increase the CDW content when compared to conservationist systems of agricultural production, such as no-till farming and crop-livestock integration. It is important to emphasize that the assessment of DF is fundamental in soil management, as it is directly related to the stability of soil microstructure and erosive processes (IGWE; OBALUM, 2013). Increased CDW potentiates the formation of surface crusts in the soil, reducing infiltration capacity and hydraulic conductivity (DIDONÉ et al., 2015).

Table 3 shows the average values for the physical attributes TP, Mac, Mic, ApMac, bulk density (Bd), and K_θ. It can be seen, in the 0-10 and 10-20 cm depth layers, that there was a significant difference ($p < 0.05$) for most of the attributes evaluated, as well as between layers. Higher coefficient of variation (CV) was verified for K_θ in the two soil layers evaluated, with 53.80% in both.

Regarding TP, the lowest average value was found in the ARS treatment, which differed from the other treatments evaluated. Higher TP was observed in the SF treatment, with 0.51 $m^3\ m^{-3}$ (Table 3). In the 10-20 cm depth layer, the lowest TP was observed in the ARS treatment (0.34 $m^3\ m^{-3}$) and the highest in the SF treatment (0.44 $m^3\ m^{-3}$). With the exception of the ARS treatment, the other treatments had a reduction in TP with increasing soil depth, with the highest percentage loss (13.72%) for the SF treatment. However, in all treatments and layers, it is observed that the TP values are within the acceptable range for sandy texture soils, which

Table 3 – Average values for the response variables total porosity, macroporosity, microporosity, aeration porosity in the macro pore domain, bulk density, and saturated soil hydraulic conductivity, of a Regosol under integrated and conventional crop production systems, Lagoa Seca/PB, Brazil.

Treatment	TP	Mac	Mic	ApMac	Bd ($g\ cm^{-3}$)	K_θ ($cm\ h^{-1}$)
			($m^3\ m^{-3}$)			
			0-10 cm			
M+M	0.44 b	0.09 b	0.35 ab	0.42 a	1.49 a	11.86 bc
U+M	0.48 ab	0.08 b	0.40 a	0.36 ab	1.46 a	23.71 b
SF	0.51 a	0.17 a	0.34 ab	0.35 ab	1.29 b	40.64 a
AGR	0.43 b	0.14 ab	0.29 bc	0.24 bc	1.38 ab	10.28 bc
ARS	0.32 c	0.08 b	0.24 c	0.16 c	1.51 a	1.06 c
Average	0.44 a	0.11 a	0.32 a	0.31 a	1.43 b	17.5 a
CV (%)	6.8	28.1	10.9	22.0	4.6	53.8
			10-20 cm			
M+M	0.41 a	0.09 b	0.31 ab	0.31 a	1.55 a	12.73 ab
U+M	0.43 a	0.08 b	0.35 a	0.30 ab	1.57 a	16.26 a
SF	0.44 a	0.11 b	0.33 a	0.29 ab	1.50 a	10.85 ab
AGR	0.39 ab	0.10 b	0.28 ab	0.21 ab	1.49 a	6.91 ab
ARS	0.34 b	0.14 a	0.25 b	0.17 b	1.50 a	1.26 b
Average	0.40 b	0.11 a	0.30 a	0.26 b	1.52 a	9.6 b
CV (%)	6.8	28.1	10.9	22.0	4.6	53.8

Legend: M+M – Mombaça grass + Maize; U+M – *Urochloa ruziziensis* (Stapf) R.D. Webster + Maize; SF – Secondary Forest; AGR – Conventional agriculture; ARS – Area in regeneration stage; CV – Coefficient of variation; TP – Total porosity; Mac – Macroporosity; Mic – Microporosity; ApMac – Aeration porosity in the macro-pore domain; Bd – Bulk density; K_θ – Saturated soil hydraulic conductivity. Averages followed by equal letters in the column do not differ by Tukey test ($p < 0.05$).

Source: Prepared by the authors (2022).

ranges from 0.33 to 0.60 m^3 m^{-3} (HUANG; HARTEMINK, 2020). The larger pore volume found in the soil under MS, in the 0-10 cm depth layer, is due to the level of conservation of the site and the lack of soil disturbance. Works such as those of Matias et al. (2012) and Thomazine et al. (2013) have shown that, in a forest environment, the contribution of plant material and the absence of soil tillage are the factors that directly favor an increase in total soil porosity, even in sandy soils.

Mac was higher in the SF (0.17 m^3 m^{-3}) and AGR (0.14 m^3 m^{-3}) treatments in the 0-10 cm depth layer. In the 10-20 cm depth layer, Mac was higher in the ARS treatment (0.14 m^3 m^{-3}), differing ($p < 0.05$) from the other treatments evaluated. In relation to the layer, Table 3 shows that there was no significant difference, with an average of 0.11 m^3 m^{-3} for the 0-10 and 10-20 cm depths. Note that, in some treatments, soil Mac was below the critical Mac, which is 0,10 m^3 m^{-3} (REICHERT et al., 2003), a behavior detected in the treatments M+M, U+M, and ARS in the 0-10 cm depth layer; and M+M and U+M in the 10-20 cm depth layer. In these treatments, Mac ranged from 0.08 to 0.09 m^3 m^{-3}, or 18% below the minimum restrictive limit. Low Mac values can compromise soil water infiltration and air dynamics. These data corroborate those observed by Silva et al. (2021) in Regosol under integration systems: for the authors, average Mac values above the critical limit in some treatments are due to soil structure improvement by the management system, or even by the lack of soil tillage.

Regarding Mic, it is observed that it was higher in the U+M treatment (0.40 m^3 m^{-3}) and lower in the ARS (0.24 m^3 m^{-3}) in the 0-10 cm depth layer. In the 10-20 cm depth layer, there was a reduction in Mic by 0.02 m^3 m^{-3}, not differing from the 0-10 cm depth layer ($p < 0.05$). In the ARS treatment, there was an increase of Mic at depth, with an average value of 0.01 m^3 m^{-3}, that is, without great expressiveness. For Reichert et al. (2003), Mic is an indicator of the state that the soil structure is in, serving as an evaluation parameter of soil compaction. As observed by Ribeiro et al. (2007), Mic was not adequate to explain the hydraulic behavior of Regosol, because the geometry of the pores will depend on its structure.

Higher Mic in relation to Mac in this soil evidences that the porosity consists predominantly of small pores, due to the predominance of sand and silt in its granulometry (RIBEIRO et al., 2007). In the soil of the present study, a higher predominance of fine sand was observed, in agreement with the study by Silva et al. (2021). According to Ribeiro et al. (2007), the face-to-face contact between the particles that predominate in sandy soils causes the grains of fine sand and silt to occupy the pores formed by the coarse sand particles, predominating microporosity and the process known as packing. ApMac was lower in the ARS treatment in the two soil layers evaluated, averaging 0.16 and 0.17 m^3 m^{-3}, respectively. This behavior results from the modification of the soil structure due to the removal of the surface layer for the construction of the weir adjacent to the experimental area. In the 0-10 cm deep surface layer there is greater microorganism activity and, consequently, better aeration and water conduction capacity. With increasing depth, there was a 16.12% reduction in ApMac, which correlated positively with Mic ($r = 0.885$; $p < 0.05$) (Table 4).

The Sd did not differ among the treatments evaluated; however, the average values were higher in the 10-20 cm layer, with 1.52 g cm^{-3} (Table 3). Despite the increase in depth, it can be seen that all average values were below the critical value for sandy texture soils, which, according to Bruand et al. (2005), ranges from 1.11 to 1.78 g cm^{-3}. In the 0-10 cm depth layer, the Sd was 19.66% below the critical bulk density (Bdc), while in the 10-20 cm depth layer, the Sd

Table 4 – Pearson correlation coefficient (*r*) for physical attributes of a Regosol under integrated and conventional crop production systems, Lagoa Seca/PB, Brazil.

	TP	Mac	Mic	ApMac	Bd	$K_θ$
TP	1	0.224	0.869	0.823	-0.522	0.891
Mac		1	-0.219	-0.152	-0.783	0.891
Mic			1	0.885	-0.121	0.690
ApMac				1	-0.187	0.664
Sd					1	-0.649
$K_θ$						1

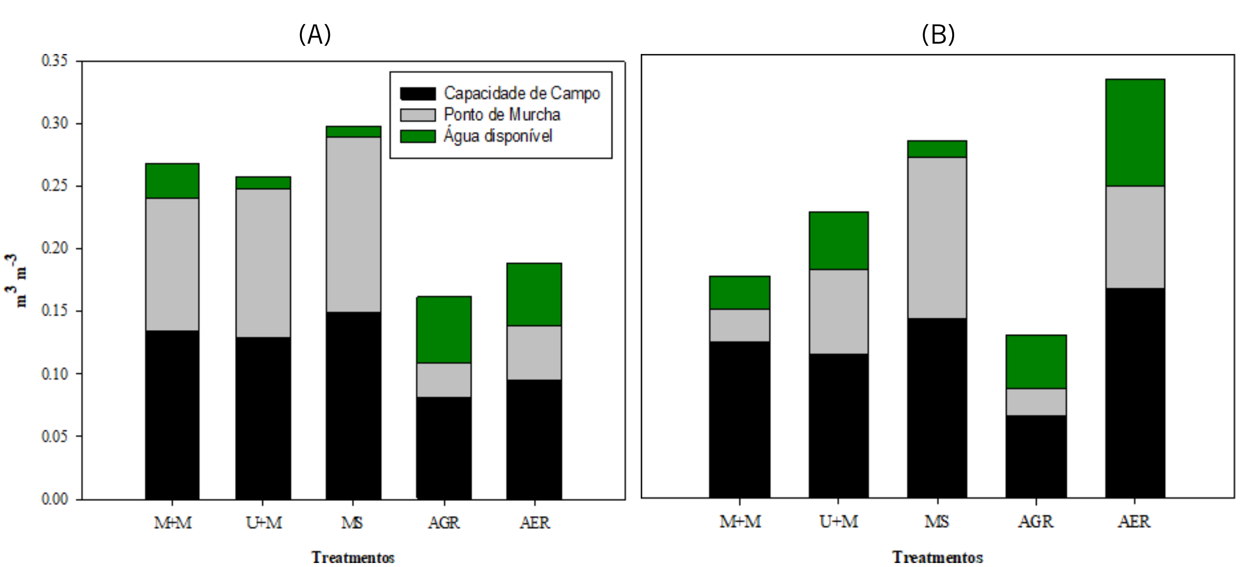
Legend: TP – Total porosity; Mac – Macroporosity; Mic – Microporosity; ApMac – Aeration porosity in the macropore domain; Bd – Bulk density; $K_θ$ – Saturated soil hydraulic conductivity.

Source: Prepared by the authors (2022).

was 14.60% lower than the Sdc. These results show that, taking into account Sd as an indicator of soil quality, it can be said that the soil has no limitations for plant development. Regarding the correlation coefficient, it is observed that the Sd has a negative correlation with TP (r = -0.522; $p < 0.05$) and with Mac (r = -0.783; $p < 0.05$), demonstrating the negative effect of this attribute on soil structure.

For the saturated soil hydraulic conductivity ($K_θ$), greater physical limitation is seen in the 0-10 cm layer (1.06 cm h^{-1}) and 10-20 cm depth (1.26 cm h^{-1}) for the ARS treatment. This result indicates that the removal of the topsoil compromised its structure, causing surface runoff by suppressing the conductive pores (Mac). From surface to subsurface, there was a 54.85% reduction in $K_θ$, with consequences for soil water storage in the 10-20 cm depth layer. At 0-10 cm depth, the highest $K_θ$ was seen in the SF treatment (40.64 cm h^{-1}) and reduced to 10.85 cm h^{-1}, which is equivalent to -73.30% in water conduction capacity for this soil, the largest loss among the treatments evaluated.

Figure 2 – Field capacity, permanent wilting point, and available water of a Regosol under integrated and conventional crop production systems, Lagoa Seca/PB, Brazil. A) 0-10 and, B) 10-20 cm depth.



Source: Prepared by the authors (2022).

Figure 2 shows the results for θ_{FC}, θ_{PWP}, and θ_{AW} for the different treatments evaluated. The θ_{FC} in both soil layers (Figure 1 A, B) was above the critical limit, which, according to Yost and Hartemink (2019), ranges from 0.05 to 0.220 m^3 m^{-3}, as does the θ_{PWP} which ranges from 0.01 to 0.07 m^3 m^{-3}.

In the 0-10 cm depth layer, the lowest θ_{FC} and θ_{PWP} values were observed in the AGR treatment. This behavior was due to the modification of the soil structure caused by soil preparation before sowing. As observed by Costa et al. (2009), in conventional systems, the use of agricultural implements such as plow, scarifier or harrow tends to reduce the θ_{FC} of the soil. The same trend was verified in the 10-20 cm depth layer, however, the θ_{PWP} was below that considered adequate for the plants, with 0.05 m^3 m^{-3}. This result reflects on the availability of water, with possible harmful effects from water deficit. In the 10-20 cm depth layer, there was a reduction in θ_{FC} and θ_{PWP} compared to the 0-10 cm layer (Figure 2). All θ_{FC} values remained above the critical limit, however, the behavior of θ_{PWP} draws attention due to the average value close to zero.

The treatments with M+M and U+M integration systems and SF have θ_{FC} values very close to θ_{PWP}, thus reflecting very low, and in some cases even unavailable, θ_{AW} values for most of the cultivated species. As presented in Figure 3C, the average θ_{AW} values were below what is considered adequate (> 0.200 m^3 m^{-3}) (REYNOLDS et al., 2007), especially for the M+M, U+M, SF, and AGR treatments. In these treatments, θ_{AW} was below 0.10 m^3 m^{-3}, considered by Hall et al. (1977) as poor or unavailable to plants. In the ARS treatment, satisfactory results were obtained for θ_{AW} in both soil layers, however, 40.90% below what is considered "ideal". When the soil water content ranges from 0.10 to 0.15 m^3 m^{-3}, Reynolds et al. (2007) classify the soil as poor in water availability; thus, it can be stated that all treatments are considered critical. The average value of available water for the two layers (summation) is well below what is considered ideal, even for the treatments under crop-livestock integration, such as M+M and U+M. The average values of available water were 82.5, 87.5, 86.0, 77.5, and 42.5% below what is considered adequate for the M+M, U+M, SF, AGR, and ARS treatments, respectively.

Conclusions

The crop-livestock integration systems did not modify the physico-hydric quality of the soil, when compared to each other. However, compared to the conventional system, it is noticeable that there were considerable improvements of TP, Mic, ApMac, and K_θ. It is concluded that long-term studies are still needed to verify the effect of integration systems on maintaining the quality of sandy soils in a semiarid climate environment.

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