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Physical properties of Ferralsols in response to sugarcane cultivation in the state of Goiás, Brazil

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ABSTRACT. For sugarcane production, soil physical properties are essential indicators of crop growth, development and sustainable productivity. This study evaluated the physical properties of different textural classes of *Latossolos Vermelhos distróficos* (Ferralsols) under sugarcane cultivation, with and without vinasse application. The study was conducted under the soil, climate and management conditions of the counties of Quirinópolis and Goianésia, both in Goiás State, Brazil. In Quirinópolis, variety RB 867515 was planted and evaluated over 1, 3, and 7 consecutive sugarcane cycles. In Goianésia, cv. CTC4 was cultivated and assessed in 1, 2, and 4 cycles. At both locations, a plot with native vegetation was used as reference. To evaluate bulk density, macroporosity, microporosity, total porosity, macro- to micropore ratio, soil aeration capacity and relative bulk density, soil samples were collected from the 0.0-0.10, 0.10-0.20, 0.20-0.30, and 0.40-0.50 m layers. It was found that soil physical properties were affected by the crop cycles, and in Quirinópolis, the plots in the first and third cycles were most affected by increased bulk density. In Goianésia, the physical properties were negatively affected in the first and second sugarcane cycles. Regardless of the soil texture and vinasse application, the soil physical properties were negatively affected by the implementation or renewal of sugarcane plantations up to the third consecutive sugarcane cycle, but improved from the fourth to the seventh cycle without sugarcane renewal.

Keywords: *Saccharum* spp.; bulk density; Cerrado biome; soil management; soil porosity; soil structure.

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Introduction

A study of the physical properties of soils under sugarcane cultivation showed a direct relationship between crop growth, development and yield. These properties are affected by management practices such as soil tillage, vinasse application and cane field renewal. Therefore, they are commonly used as indicators of soil physical quality and productive capacity (Ramos et al., 2020).

Data of soil physical properties such as texture, bulk density, mechanical penetration resistance, porosity, among others, are important for explaining phenomena related to crop productivity, caused by changes in the management system (Tavares et al., 2010; Baquero et al., 2012; Oliveira et al., 2015). However, the dynamics of these properties are defined by the soil type, management conditions, carbon input and the renewal time of sugarcane plantations, which could require immediate and long-term monitoring (Laurindo et al., 2009; Silva et al., 2017).

From soil tillage to harvest, sugarcane production depends on the use of agricultural machinery at several stages (Baquero et al., 2012). This can cause soil degradation (Silva & Castro, 2015; Marasca et al., 2015; Vischi Filho et al., 2015), and affect the yields and longevity of a sugarcane plantation (Camilotti et al., 2005; Silva Junior et al., 2013; Fagundes et al., 2014). In light of this, adequate planning of the agricultural activities involved in the sugarcane production system, including soil tillage, planting and harvesting, is fundamental to harvesting a satisfactory quantity and quality of raw materials (Baquero et al., 2012; Arcoverde et al., 2019).

Vinasse is a by-product of ethanol (alcohol), butanol and brandy, frequently applied in sugarcane plantations and distributed through the irrigation system. Vinasse consists mostly of organic matter in the form of organic acids and, to a minor extent, of cations such as potassium (K^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}). When properly applied at about 150 m^3 ha^{-1}, vinasse fertilization is equivalent to 61 kg ha^{-1} N, 40 kg ha^{-1} P, 343 kg ha^{-1} K, 108 kg ha^{-1} Ca and 80 kg ha^{-1} S (Medeiros, 2003). The use of this organic compound as fertilizer does not only alter the soil nutrient concentrations but also the physical properties (Silva et al., 2005; Barros et al., 2010).

In view of this, few studies have evaluated the effects of crop systems on the physical quality of soils under sugarcane cultivation, mainly for soils with high compaction potential such as *Latossolos* (Ferralsols, in the World Reference Base for Soil Resources), with a clayey texture (Silva & Castro, 2015).

Therefore, this study hypothesized that mechanized agricultural practices on sugarcane plantations contribute to degradation of soil physical quality, regardless of soil management and texture. Thus, this study evaluated the physical properties of *Latossolos Vermelhos distróficos* (LVd) with different texture classes under sugarcane cultivation, with and without vinasse application.

Material and methods

Experimental area

This study was carried out on a commercial sugarcane plantation, from February to April 2019, in Quirinópolis (South of Goiás State, Brazil, 18°33'50.65" S, 50°26'10.06" W; 579 m asl) and in Goianésia (Center of Goiás State, Brazil, 15°12'48.24" S, 48°59'04.91" W; 650 m asl) (Figure 1).

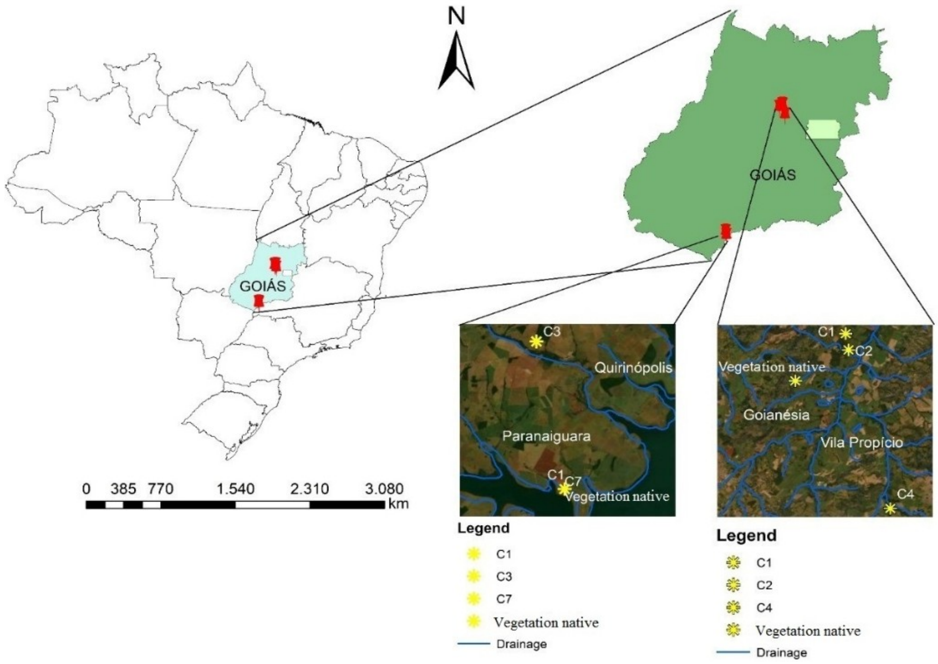

Figure 1. Location of the study areas in the Midwest region of Brazil, in the counties of Quirinópolis and Goianésia, Goiás State, Brazil. Source: (Instituto Brasileiro de Geografia e Estatística [IBGE], 2018) and QGIS (2021), version 3.16.2.

Based on the Köppen classification, the climate of both regions was classified as AW (Alvares et al., 2013). The annual rainfall and temperature means in Quirinópolis and Goianésia were 1,531 mm and 24.3°C, and 1,442 mm and 24.4°C, respectively (Instituto Nacional de Meteorologia [INMET], 2021). The climatological normal (year: 2019) was obtained from the database of Xavier (2020). It included rainfall and maximum, mean and minimum temperature, for a better understanding of the climate regarding the environmental effect on sugarcane management in the region (Figure 2).

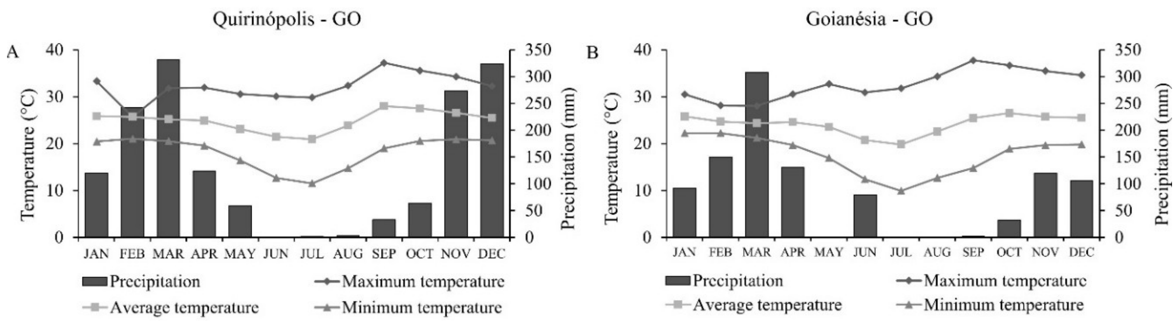

Figure 2. Climatological normal (year: 2019), rainfall and air temperature of the counties where the study was carried out, Goiás State, Brazil, 2020.

Characterization and history of the study region

The soils of the areas were characterized as Ferralsols, according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2022) or *Latossolos Vermelhos distróficos* (LVd) according to the Brazilian Soil Classification System (Santos et al., 2018), with a medium texture in Quirinópolis and clayey texture in Goianésia. Soil samples for classification were collected as proposed by the Soil Description and Collection Manual in the Field (Santos et al., 2015) and the Technical Manual of Pedology (IBGE, 2015).

Study plots were selected based on information provided by farmers. Plots with the greatest possible homogeneity in terms of soil texture, cultivated variety and management system were selected. However, the length of the sugarcane cycles was different in Quirinópolis: C1- sugarcane with 1 sugarcane cycle; C3 - sugar cane with 3 sugarcane cycles and C7 - sugar cane with 7 sugarcane cycles. In Goianésia, the cycles were: C1- sugarcane with 1 sugarcane cycle; C2 - sugarcane with 2 sugarcane cycles and C4 - sugarcane with 4 sugarcane cycles. As reference area, in both plantations, a plot of native vegetation (NV) close to the commercial cultivation plots was selected for comparison (Table 1).

Table 1. History and location of the study plots.

Sugarcane cycles	Description
	Quirinópolis
C1	Plot C1, one crop cycle of variety RB 867515, on the Barra do Alegre farm (18°47'32.48" S, 50°26'24.27" W; 416 m asl), planted on 03/27/2018, in a conventional cropping system, with vinasse fertigation; plot size 23.95 ha^{-1}. Stalk yield 94.75 t ha^{-1}, in the 2018/2019 growing season.
C3	Plot C3, three crop cycles of variety RB 867515, on the Fratari farm (18°41'9.85" S, 50°27'35.24" W; 518 m asl), planted on 09/01/2015 under conventional management and vinasse fertigation; plot size 22.75 ha^{-1}. Stalk yield 83.39 t ha^{-1}, in the 2018/2019 growing season.
C7	Plot C7, seven crop cycles of variety RB 867515, on the Campos farm (18°47'32.45" S, 50°26'24.27" W; 570 m asl), planted on 04/03/2012, in a conventional cropping system, under vinasse fertigation; plot size 23.95 ha^{-1}. Stalk yield 79.94 t ha^{-1}, in the 2018/2019 growing season.
Native vegetation	Reference plot, under native Cerrado vegetation (NV) without anthropogenic disturbance, on the Campos farm (18°47'32.45" S, 50°26'24.27" W; 593 m asl),
	Goianésia
C1	Plot C1, one crop cycle of variety CTC 4, on the 76 farm (15°5'43.03" S, 48°54'29.08" W; 602 m asl), block 1, planted on 04/16/2018, in a conventional cropping system, plot size of 47.76 ha^{-1}. Stalk yield 123.18 t ha^{-1} in 2018/2019.
C2	Plot C2, two cycles of variety CTC4, on the 76 farm, block 2 (15°5'21.24" S and 48°54'13.22" W; 592 m asl), planted on 08/07/2017, in a conventional cultivation system, plot size 44.19 ha^{-1}. Stalk yield 117.43 t ha^{-1} in 2018/2019.
C4	Plot C4, four cycles of variety CTC4, on the 84 farm (15°23'17.01" S and 48°50'8.6"W; 579 m asl), block 6 planted on 02/17/2014, in a conventional cultivation system, plot size 23.95 ha^{-1}. Stalk yield 96.94 t ha^{-1} in the 2018/2019 growing season.
Native vegetation	Native vegetation without anthropogenic interference. (15°14'28.00" S, 48°59'24.00" W; 640 m asl).

Plots of *Latossolo Vermelho distrófico* medium textured and clayey, growing sugar cane for 1 cycle (C1); 2 cycles (C2); 3 cycles (C3); 4 cycles (C4); 7 cycles (C7) and native vegetation (NV).

Aspects of soil management in Quirinópolis

Plots C1 and C3 had both been replanted once, whereas C7 had still not been renewed in the seventh cycle. Prior to sugarcane cultivation, the predominant activity in the region was low-technology livestock rearing on degraded pastures. After the reform of the cane fields, soybean (*Glycine max*) was cultivated for one growing season and after the harvest, sugarcane was planted directly on the legume straw.

The required amount of limestone was calculated based on the recommendation for the crop, and each plot received dolomitic limestone as follows: C1 (2.10 t ha^{-1}), C3 (2.20 t ha^{-1}), and C7 (3.32 t ha^{-1}). The limestone was incorporated into the soil with a moldboard plow, followed by a leveling harrow. After crop establishment, agricultural gypsum was also applied to plots C3 and C7 at 1.10 and 1.00 t ha^{-1} and distributed by broadcast. In plot C3, gypsum was applied as in the previous cycle in 2014, without any further applications.

During reinstallation of the sugarcane plantations, the stumps were removed with 340 HP tractors weighing 10 tons, using a 36-inch plow harrow, followed by subsoiling to a depth of 0.40 m. Harvesting was carried out mechanically with a 358-HP sugarcane harvester (mean weight 20 t), and a 235-HP tractor (18 t ha^{-1}) pulling sugarcane wagons (5 t).

Fertilization in C1 consisted of 50 kg ha^{-1} monoammonium phosphate, 230 kg ha^{-1} urea, 65 kg ha^{-1} potassium chloride, 3.6 kg ha^{-1} boric acid and 4.5 kg ha^{-1} zinc sulfate and was applied in the furrow. In C3, 500 kg ha^{-1} of the granular fertilizer 20-05-19 was applied and in C7, 660 kg ha^{-1} of the granular fertilizer 08-25-11 was applied. It is worth noting that fertilization in the ratoons, both in the first and subsequent cycles, was applied according to the crop requirements and estimated productivity. It is also worth remembering that all plots were treated annually with vinasse at 100 m^3 ha^{-1}.

Soil management in Goianésia

Plots C1, C2, and C4 had been renewed 5, 3, and 3 times, respectively. Prior to sugarcane cultivation, native vegetation was predominant in the study area. After removing the sugarcane plantations, soybean (*Glycine max*) was planted in the plots for one season, followed by sorghum. After the harvest, sugarcane was planted directly on the crop straw. The amount of limestone was calculated according to recommendations for the crop, with a mean of 1 t ha^{-1} of dolomitic limestone, incorporated into the soil with a moldboard plow, followed by a leveling harrow.

During reinstallation of the sugarcane plantations, the stumps were removed by 200-HP tractors (10 t) using a 36-inch plow harrow, followed by subsoiling to a depth of 0.45 m. Harvesting was done mechanically with a 140-HP harvester (mean weight of 20 t). Fertilization was applied in the planting furrow according to the expected crop productivity of more than 100 t ha^{-1}, at rates of 80-100 kg ha^{-1} of N-P-K.

In the first two years, these plots were watered with 60 mm irrigation. Thereafter, irrigation was suspended and the cultivation system depended on rainfall.

For the physical characterization (particle-size analysis) of soil in the experimental areas, samples were collected with a Dutch auger from the 0-0.10, 0.10-0.20, 0.20-0.30, and 0.40-0.50 m layers. Soil was randomly collected from three randomly drawn locations out of 30 possible for each system. The labelled soil samples from the field were air-dried on plastic trays, then sieved (<2 mm) for granulometric analysis. This study utilized the soil fraction that passed through a 2 mm sieve, also called air-dried fine soil (ADFS) (Table 2). Particle density (Pd) was determined using the same samples.

To calculate particle density (Pd), 20 g of air-dried (105°C, 24h) ADFS from each system was placed in a volumetric flask. After adding 25 mL of ethyl alcohol, the liquid was stirred and covered. After 24h, the volumetric flask was filled to 50 mL with ethyl alcohol, and the added volume was recorded.

Table 2. Chemical and particle-size characterization in different sugarcane cultivation cycles.

Crop cycles	CS	FS	Si	Clay
	----------------	g kg^{-1}	----------------	
		Quirinópolis		
		0-0.10 m		
C1	337	363	104	196
C3	412	396	50	142
C7	393	316	106	185
NV	494	220	103	183
		0.10-0.20 m		
C1	347	347	94	212
C3	412	404	39	145
C7	327	350	95	228
NV	181	518	109	192
		0.20-0.30 m		
C1	324	345	96	235
C3	383	416	37	164
C7	313	365	80	242
NV	153	538	110	199
		0.40-0.50 m		
C1	251	410	86	253
C3	365	413	26	196
C7	291	365	94	250
NV	140	527	102	231
		Goianésia		
		0-0.10 m		
C1	130	309	74	487
C2	188	371	22	419
C4	90	433	25	452
NV	55	245	130	570
		0.10-0.20 m		

C1	131	310	69	490
C2	152	401	18	429
C4	76	443	24	457
NV	36	237	158	569
		0.20-0.30 m		
C1	144	293	66	497
C2	184	373	12	431
C4	74	417	48	461
NV	32	243	148	577
		0.40-0.50 m		
C1	111	297	64	528
C2	163	352	39	446
C4	76	398	45	481
NV	21	213	166	600

(1)CS: coarse sand, FS: fine sand, Si: silt, Clay: clay, C1: plot of 1st sugarcane cycle, C2: plot of 2nd sugarcane cycle, C3: plot of 3rd sugarcane cycle, C4: plot of 4th sugarcane cycle, C7: plot of 7th sugarcane cycle and NV: native vegetation plot.

Soil sampling and measurement of physical properties

For the determination of bulk density (Bd), macroporosity (Ma), microporosity (Mi), total porosity (TP), macro- and microporosity ratio (Mac:Mic), relative density (Rd) and soil aeration capacity (SAC), three undisturbed soil samples were collected from a mini trench (0.6 x 0.4 x 0.6 m length, width and depth, respectively) at each sampling point. The trenches were dug about 0.30 m away from the sugarcane row, and soil was extracted in volumetric rings (stainless steel, 0.05 m diameter and 0.05 m height), from the 0-0.10, 0.10-0.20, 0.20-0.30, and 0.40-0.50 m layers. After removing the auger, excess soil was removed from the rings which were then wrapped in PVC film, labeled and placed in plastic boxes. Thus, at each sugarcane mill, 144 rings were collected (four systems x three points per system x four layers x three repetitions per layer).

The soil samples were placed in a tray, saturated by capillarity, filled with water to 2/3 height of the volumetric rings, and weighed. Thereafter, the samples were subjected to voltages of -10, -30, -60, and -100 hPa on a tension table and the respective weights were recorded after these treatments and at negligible drainage values. At the end, the samples were oven-dried (105°C) for 48h and bulk density (Ds, in g cm^{-3}) was determined as the ratio between dry soil weight and total volume (Teixeira et al., 2017). In order to normalize the limits of Ds, depending on the soil texture and other properties, the concept of relative bulk density (Rd) or compaction degree was used (Beutler et al., 2005; Klein, 2006).

Macroporosity (Ma, in dm^3 dm-^{3}) was calculated as the difference between total soil porosity (TP, in dm^3 dm^{-3}) (Silva & Azevedo, 2001) and moisture at equilibrium with a potential of -60 hPa, according to Equation 1:

$$Ma = Tp - W_{-60\ hPa} \quad (1)$$

where W_{-60} is the water content at a matric potential of -60 hPa, obtained in the determination of the water retention curve in the soil and TP the total porosity. Microporosity (Mi, in dm^3 dm^{-3}) was determined at the soil water content retained at a voltage of 60 hPa (Santos et al., 2011).

The total porosity of the soil (TP, in dm^3 dm^{-3}), or total pore volume was calculated with Equation 2:

$$TP = 1 - \left({}^{Bd}/_{Pd}\right) \quad (2)$$

where Bd is the soil bulk density (g cm^{-3}) and Pd the soil particle density (g cm^{-3}) (Teixeira et al., 2017).

The variable soil aeration capacity (SAC) was determined by the relationship reported by Reynolds et al. (2002), as presented in Equation 3:

$$SAC = TP - FC/TP \quad (3)$$

where TP is the total soil porosity (dm^3 dm^{-3}) and FC the field capacity, considered equal to the soil water content at a voltage of 100 hPa (dm^3 dm^{-3}).

Statistical analysis

The results of the soil physical properties were analyzed by descriptive data analysis, which showed that the assumptions of independence were satisfied and those of error homoscedasticity and normality were evaluated using the Shapiro-Wilk test (Torman et al., 2012). Thereafter, the Scott-Knott test was conducted at 5% probability ($p < 0.05$), using Sisvar version 5.7 (Ferreira, 2014). Polynomial regression was used to evaluate relative bulk density (Rd), and Microsoft Excel was used to draw the figures.

Results

After evaluating the physical properties of medium-textured soil in Quirinópolis, treated with vinasse applied by a self-propelled irrigation equipment, in comparison with native vegetation (NV), changes were observed in response to the crop cycles (C1, C3, and C7) (Figure 3). For bulk density (Bd), the negative effect was greatest in C1 and C3 in the 0-0.10, 0.10-0.20, and 0.20-0.30 m layers and in C3 in the 0.40-0.50 m layer (1.72 g cm^{-3}). In plot C7, with the longest management period, Bd was lowest in all studied layers (Figure 3A).

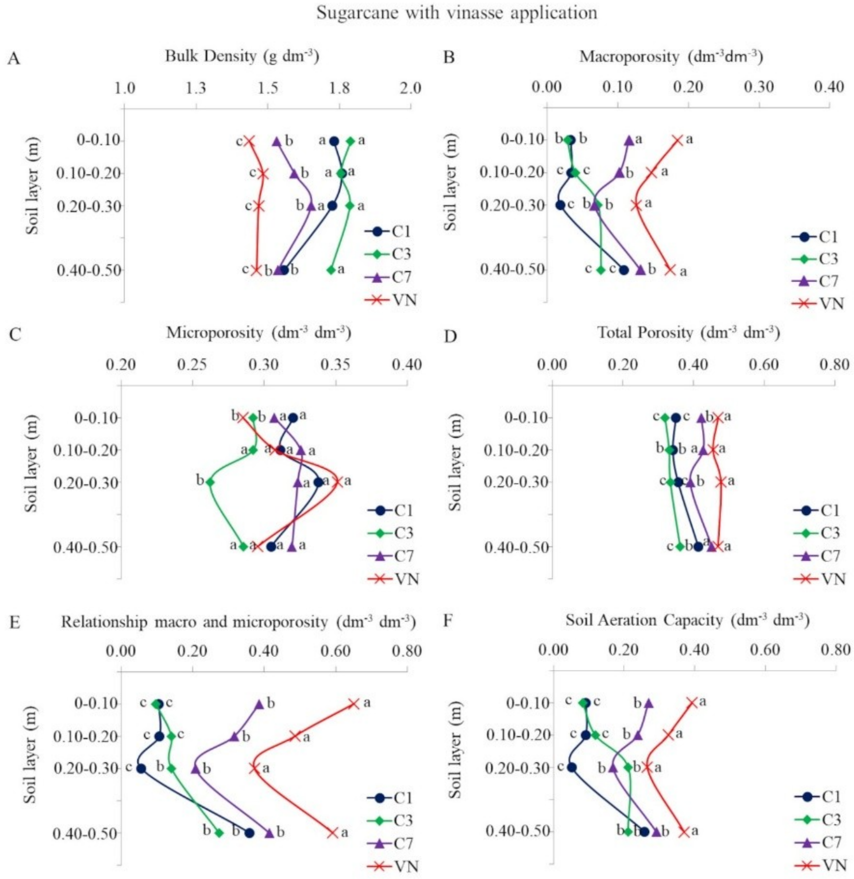

Figure 3. Bulk density (A), macroporosity (B), microporosity (C), total porosity (D), macro- to micropore ratio (E) and soil aeration capacity (F) in different layers of a medium textured *Latossolo Vermelho distrófico*, fertigated with vinasse, over different sugarcane production periods (C1: one crop cycle; C3: three crop cycles; C7: seven crop cycles and NV: native vegetation), in Quirinópolis, Goiás State, Brazil. Different lowercase letters between sugarcane planting times in the same layer indicate statistical differences by the Scott-Knott test ($p < 0.05$).

For macroporosity (Ma), the lowest values were observed in C1 and C3, in the layers 0-0.10 m (0.03 and 0.02 dm^3 dm^{-3}, respectively), 0.10-0.20 m (0.03 and 0.04 dm^3 dm^{-3}, respectively), and 0.40-0.50 m (0.11 and 0.08 dm^3 dm^{-3}, respectively), and in C1, in the layer 0.20-0.30 m (0.02 dm^3 dm^{-3}) (Figure 3B). In all evaluated layers, macroporosity was highest in C7.

For microporosity (Mi), there was no significant difference between the sugarcane cycles in the 0.10-0.20 and 0.40-0.50 m layers. In the other layers (0-0.10 and 0.20-0.30 m, respectively), Mi was lowest in the plot with the 3-year crop cycle. Moreover, plots C1 and C7 recorded a greater positive effect on this property than NV (Figure 3C).

For total soil porosity (TP), the different sugarcane cycles were observed to have an influence. In plots C1 and C3, TP was lowest in the layers 0-0.10 m (0.35 and 0.32 dm^3 dm^{-3}, respectively), 0.10-0.20 m (0.34 and 0.33 dm^3 dm^{-3}, respectively), and 0.20-0.30 m (0.35 and 0.33 dm^3 dm^{-3}, respectively). In these plots the effect on soil aeration was greatest, and in plot C3, it was in the layer 0.40-0.50 m, (0.36 dm^3 dm^{-3}). In the plot with the longest cultivation period (C7), TP was highest in all layers compared to the other plots cultivated in the study (Figure 3D).

Regarding the macro- and microporosity ratio (Mac:Mic), plots C1 and C3 recorded the lowest proportion of pores in the layers 0-0.10 m (0.10 and 0.09 dm^3 dm^{-3}, respectively), 0.10-0.20 m (0.11 and 0.14 dm^3 dm^{-3}, respectively) and 0.40-0.50 m (0.35 and 0.27 dm³ dm⁻³, respectively). In the 0.20-0.30 m layer, Mac:Mic was lowest in C3 and C7 but the pore volume was highest in C7 in all layers (Figure 3E).

The plots with the lowest soil aeration capacity (SAC) were C1 and C3, in the layers 0-0.10 m (0.09 and 0.08 dm^3 dm^{-3}, respectively), 0.10-0.20 m (0.09 and 0.12 dm^3 dm^{-3}, respectively), and in C1, in the 0.20-0.30 layer (0.05 dm^3 dm^{-3}). In the 0.40-0.50 m layer, there were no differences between plots, except when compared to native vegetation. However, SAC was highest in the plot with most crop cycles in all layers (Figure 3F).

When compared with native vegetation, it was concluded that the physical properties of the *Latossolo Vermelho distrófico* with a clayey texture and without vinasse application, were altered in response to the sugarcane cycles (Figure 4). In all evaluated layers, bulk density was highest in plot C2, but under successive sugarcane cycles in C4, Bd was least affected in comparison with the NV plot (Figure 4A).

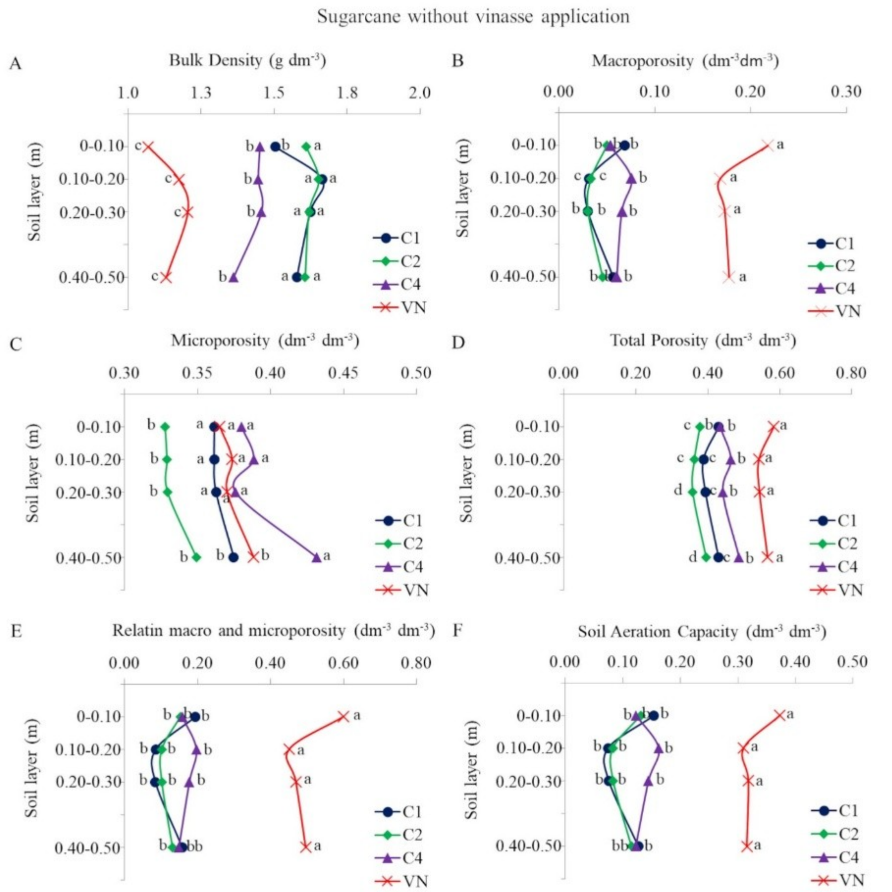

Figure 4. Bulk density (A), macroporosity (B), microporosity (C), total porosity (D), macro and micropore ratio (E) and soil aeration capacity (F) in different layers of a clayey texture *Latossolo Vermelho distrófico*, without vinasse application, over different sugarcane production periods (C1: one crop cycle; C2: two crop cycles; C4: four crop cycles and NV: native vegetation), in Goianésia, Goiás State, Brazil. Different lowercase letters between sugarcane planting times in the same layer indicate statistical differences by the Scott-Knott test $p < 0.05$).

Of all the soil porosity properties (Ma, Mi, TP, Mac:Mic and SAC) considered in the different sugarcane cycles, it was only the Mac:Mic ratio and SAC that did not differ between the cultivated plots but differed in comparison with NV. There was no difference in macroporosity among the cultivated plots, except in the 0.10-0.20 m layer, with lower values in plots C1 (0.03 dm^3 dm^{-3}) and C2 (0.03 dm^3 dm^{-3}) and a higher mean value in C4 in all layers (Figure 4B).

For microporosity, the highest values were observed in C2 in all studied layers. The plots with the highest proportions of Mi were recorded in C1 and C4 in the layers 0-0.10 m (0.36 and 0.38 dm^3 dm^{-3}, respectively), 0.10-0.20 m (0.36 and 0.33 dm^3 dm^{-3}, respectively) and 0.20-0.30 m (0.36 and 0.37 dm^{-3} dm^{-3}, respectively), and in C4 in the layer 0.40-0.50 m (0.43 dm^3 dm^{-3}) (Figure 4C).

The plots with the lowest total porosity were C2 in the 0-0.10 m layer (0.38 dm^3 dm^{-3}) and C1 and C2 in the 0.10-0.20 m layer (0.38 and 0.36 dm^3 dm^{-3}, respectively). In the layers 0.20-0.30 m and 0.40-0.50 m, the TP values were lowest in C2. The plot with the longest sugarcane cycle (C4) was the one with the highest concentration of pores in all evaluated layers (Figure 4D).

According to the different sugarcane cycles (Figure 5), different values of relative bulk density (Rd) were recorded for the *Latossolos* (Figure 5). However, a downward trend in Rd was observed over the course of the cycles, with the lowest Rd recorded in plots C4 and C7 in all layers.

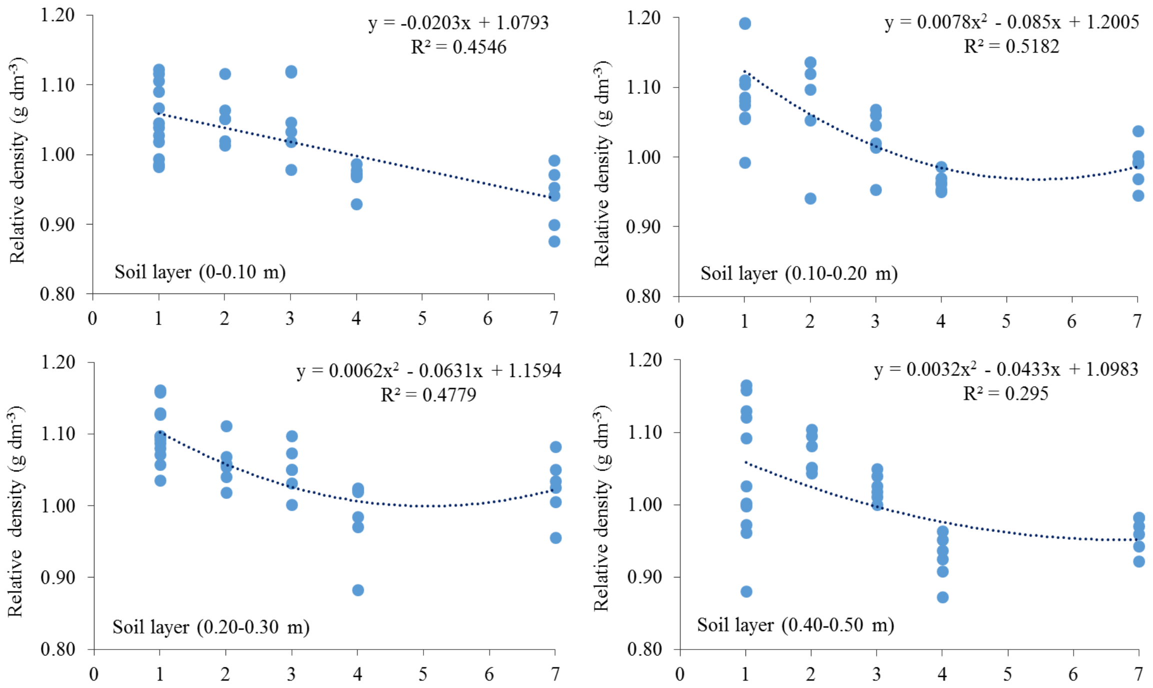

Figure 5. Relative bulk density in different layers of *Latossolo Vermelho distrófico*, with medium and clayey texture, with and without vinasse application, over different sugarcane cycles (C1: one crop cycle; C2: two crop cycles; C3: three crop cycles; C4: four crop cycles and C7: seven crop cycles), in the municipalities of Quirinópolis and Goianésia, Goiás State, Brazil.

Discussion

Effect of vinasse application on the structural quality of soil under sugarcane cultivation

Vinasse was applied by fertigation, and it improved the soil physical properties. According to Giachini and Ferraz (2009), the use of vinasse in agricultural plots, especially in sugarcane plantations, has unquestionable benefits from the agronomic, economic and social points of view. Moreover, some studies with sugarcane have evaluated the effect of long-term vinasse application on the physical properties of different soil types (Canellas et al., 2003; Silva et al., 2014; Yin et al., 2019) and described its benefits.

Evaluation of the soil physical properties (Figure 3) showed that the sugarcane cultivation period (1 cultivation cycle of sugarcane - C1; 3 cycles - C3; 7 cycles - C7) influenced the physical quality of the soil compared to the native vegetation (NV). Plots C1 and C3 were compacted, however, throughout the cultivation period the compaction decreased, such that in plot C7 the physical characteristics were restored.

In the plot under native vegetation, the soil properties were least affected and this was attributed to the greater accumulation of plant residues on the soil surface, and organic carbon in the surface layers and to less anthropogenic disturbance (Torres et al., 2008; Castioni et al., 2018).

Changes in the soil physical properties of cultivated plots compared to native vegetation are due to agricultural operations in the sugarcane plantations, such as soil tillage, cultural practices, plowing and harvesting, and may cause soil degradation (Ceddia et al., 1999; Prado et al., 2014). Another factor that affects soil properties is the pressure of agricultural machinery and implements on the soil (Marsili et al., 1998).

Obtaining the highest values of Bd in C1 and C3 indicated that C1 and C3 were the most compacted plots, which resulted from machine traffic and the intensive oxidation of organic matter in the early years. Intensive cultivation associated with soil disturbance, common in the conventional system, is responsible for the low content of organic matter in agricultural plots (Pereira & Thomaz, 2014).

The increase of Bd in the study plots promoted a decrease in properties related to soil aeration, such as Ma, Mi, TP, Ma:Mi and SAC in all soil layers. Numerous studies have reported an increase in Bd and a decline in TP and Ma in the soil of cultivated plots compared with the native vegetation (Centurion et al., 2007; Castro et al., 2013; Albert et al., 2018).

Based on the soil texture of the plots, only C7 was within the Bd limits considered ideal for cultivation. Over time, there were structural improvements in the soil given by the reduction of this property, resulting from a biological decompression, which was probably promoted by root renewal and biological activation of the soil fauna and microbiota.

Considering the environments, the least compromised in comparison with NV was C7, with lower Bd values and higher proportions of Ma, Mi, TP, Mac:Mic and SAC. This behavior is probably due to soil restructuring over time, which promoted improvements quantified by the reduction of Bd and the increase in properties related to soil aeration (Ma, Mi, TP, Mac:Mic, and SAC).

Macroporosity exceeded the critical limit in plots C7 and NV, with higher values under NV. The critical limit is well defined in the literature (Dexter, 1988; Andrade & Stone, 2009), at a minimum threshold of 0.10 $m^3 m^{-3}$. In addition to the effect of vinasse, the high Ma in C7 could be related to the physical regeneration of the soil over time.

The high Ma of the soil under NV may be related to the greater root mass provided by the vegetation and possible channels (biopores) resulting from the decomposition and renewal of these roots (Lima et al., 2012). While evaluating the effects of different management systems with sugarcane on the physical-hydric properties of a cohesive *Argissolo Amarelo*, Silva et al. (2005) found a significant reduction in total porosity and macroporosity but there was increased microporosity of soils under rainfed, irrigated and vinasse-fertigated cultivation, compared to soil under native vegetation.

In all studied layers, the lowest Ma values were recorded in plots C1 and C3. In both plots, root growth was below the minimum threshold in 0-0.10 and 0.10-0.20 m, and in the deeper layers (0.20-0.30 and 0.40-0.50 m), no differences were observed. Sugarcane is one of the crops most affected by changes in soil physical conditions. This is because mechanized harvesting can cause soil compaction, thereby promoting reductions of more than 50% in the Ma volume of a soil (Santos et al., 2020). Consequently, this structural change can compromise the sustainability of this agricultural activity, due to the high erosive capacity of rainfall (Anjos et al., 2020), and Ma also determines the rate of soil water movement (Oliveira et al., 2013).

The greatest increase in microporosity for soil under agricultural use was recorded in C7, in all studied layers. This property must be monitored carefully during cultivation management, since these pores retain the water available for plants (Severiano et al., 2009). According to Lima et al. (2007), the ideal Mi values varied between 0.25 and 0.33 $m^3 m^{-3}$. Generally, it is noteworthy that low Mi values were obtained for all assessed plots. This is common in this soil class, since pore space distribution is directly related to granulometry (Ramos et al., 2020).

Total porosity is directly affected by bulk density (Ramos et al., 2020). This property has been used to determine the changes caused by different management systems, or even as indicators of soil quality (Matias et al., 2009; Oliveira et al., 2015). In the study plots, some values exceeded the critical limits that ensure an appropriate physical quality of sandy soils in all layers. According to scientific literature, these limits range from 0.15 to 0.34 $m^3 m^{-3}$ (Reynolds et al., 2002; Assis et al., 2015).

Total porosity was highest in plot C7 in the layers 0-0.10 and 0.10-0.20 m and there was no difference between C7 and C1 for the layers 0.20-0.30 m and 0.40-0.50 m. The plot with the highest Bd was C3, which therefore had the lowest TP. Arruda et al. (2016) evaluated bulk density and porosity in response to different tillage operations (plow + harrow; subsoiler + harrow; no-tillage; subsoiler + no-tillage; stump destroyer + subsoiler; stump destroyer + harrow + plow + moldboard plow + harrow), and found that irrespective of the tillage form, total porosity decreased and bulk density increased in ratoon cane.

The Mac:Mic ratio was highest under NV in all studied layers; however, it was only in the layers 0-0.10 and 0.40-0.50 m that the NV was within the ideal limits considered close to a Mac:Mic ratio of 0.50 (Kiehl, 1979). These properties are important physical quality indicators, as they provide information related to soil processes, such as water and nutrient dynamics, depending on the management adopted in agricultural cultivation or its behavior under native vegetation (Ampoorter et al., 2010).

Soil aeration capacity is a property that depends on the porous arrangement of the soil, and is positively correlated with saturated hydraulic conductivity, macroporosity and microporosity (Assis et al., 2015). It is a variable that needs to be well interpreted and analyzed for agricultural management, as a significant increase in soil aeration capacity above the critical limit of 0.34 $m^3 m^{-3}$ may indicate low retention capacity and water availability for the plants (Silva et al., 2018).

Soil structural behavior without vinasse application

Most soil physical properties were affected by sugarcane cultivation without vinasse application, compared to those of NV (Figure 4). The plots C1 and C2 were the most compacted, i.e., with greater impairment of physical properties in the first cycles of cultivation. These changes compared to NV in the first cycles were due to the increased intensity of land use and reduction of the vegetation cover, which led to soil degradation as regards soil chemical, physical and biological characteristics (Freitas et al., 2017).

Previous studies have reported an increase in Bd and a reduction in properties related to soil pores, such as TP and Ma in cultivated plots in relation to NV (Centurion et al., 2007; Machado et al., 2010; Albert et al., 2018). For other properties such as Mi, Mac:Mic and SAC, this increasing pattern was also observed with the increase in Bd, which can be explained by the successive effect of machine traffic during cultivation operations mainly in the first cycles, which contributed to higher Bd and lower TP values in C1 and C2.

The intense use of mechanization from planting to harvesting and sugarcane transportation, promotes an increase in Bd and structural changes. This can reduce the root system development (Kumar et al., 2012) by affecting soil porosity, air and water availability, mechanical strength (Oliveira, Rolim, Vasconselos, Costa, & Pedrosa, 2010) and water infiltration (Rossetti & Centurion, 2013), thereby causing losses in crop yield (Cavalieri et al., 2006; Moussa-Machraoui et al., 2010).

In the 0-0.10 m layer of plot C1, a higher Bd was observed, although the mean values in the other layers of this plot did not differ from those in the layers of plot C2, characterizing them as the most compacted plots (Figure 4). The cumulative effect of machine traffic on soil physical properties, especially during sugarcane harvesting in the first cycles, may have contributed to higher Bd and lower TP in these plots. This reflects in the decreasing macroporosity, macro- and microporosity ratio and soil aeration capacity, causing the roots to explore and develop in the uppermost layers (Tormena et al., 2002; Esteban et al., 2019).

Macroporosity is highly affected by the soil management system (Vischi Filho et al., 2015). In this study, Ma values in all plots were below the critical limit except for NV (Figure 4), which was directly affected by degradation or improvement of the soil structure (Bonini et al., 2015).

Also for Ma, like the pattern of results in this study, Cherubin et al. (2016) found lower macroporosity values than expected for plant growth, after evaluating plots cultivated with sugarcane under different edaphoclimatic conditions. The authors concluded that sugarcane cultivation, regardless of climatic conditions and soil texture, leads to lower macroporosity values than recommended by the literature, as was also the case in this experiment.

For Mi, the smallest increments were registered in the first sugarcane cycles in all evaluated layers. In plot C4, microporosity was higher, which can be an advantage in terms of water retention; conversely, there was loss of aeration and gas circulation, aspects that characterize compaction and loss of soil physical quality (Rossetti & Centurion, 2013). Studies have reported that this variable is also influenced by soil texture and management systems (Reinert & Reichert, 2006; Nicodemo et al., 2018). This variable is mainly associated with soil texture and structure, since clayey soils are naturally prone to compaction, due to their high plasticity and cohesion between particles, where resistance decreases due to higher moisture, leading to the formation of laminar structures and causing deformation of the original structure.

Regarding TP and SAC, plot C4 recorded the highest proportions in all layers. Kiehl (1979) reported that the ideal total porosity of a soil for agricultural production should be 0.50 $m^3 m^{-3}$, with 1/3 macropores and 2/3 micropores.

Effect of crop cycle on soil structure

Although there were differences in Rd values after comparing the different sugarcane crop cycles, it is also important to assess whether the values are limiting for normal plant development. Klein (2006) reported a Rd value of 0.71 for a normal plant development and values above 0.88 as limiting.

In response to the successive sugarcane cycles, lower Rd values were observed, indicating an improvement in soil structure (Figure 5). However, all plots had Rd values below the values considered limiting. Soil management practices that favor higher macroporosity and reduce bulk density are extremely important to maintain soil quality and sustain unrestricted plant development (Souza et al., 2019).

The compaction caused by the traffic of agricultural machinery in the cultivated plots could have contributed to the increase in Rd (Mur & Balbuena, 2014), mainly in the soil surface layers. This increase may be the result of carrying out mechanized operations without considering the soil moisture conditions.

Conclusion

The physical properties of the soil were negatively affected by the renewal or cultivation of sugarcane plantations until the third cycle of cultivation, irrespective of vinasse application and soil texture. The soil physical properties were improved from the fourth to the seventh cycle of sugarcane cultivation without renewal of the cane field, regardless of the soil texture and vinasse application.

Data availability

All data used in this research are presented in Tables 1 and 2 and Figures 3 to 5 of this article.

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References

Albert, R. P., Pinto, M. A. B., Lima, C. L. R., Santos, F. J., Sheunemann, T., & Miguel, P. (2018). Physico-mechanical properties of a Typic Hapludox in plots with different sugarcane cultivation periods. *Revista Brasileira de Ciências Agrárias*, *13*(2), 1-8. https://doi.org/10.5039/agraria.v13i2a5536

Alvares, C. A., Stape, J. L., Sentelhas, P. C., Moraes, J. L. G., & Sparovek, G. (2013). Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift*, *22*(6), 711-728. https://doi.org/10.1127/0941-2948/2013/0507

Ampoorter, E., Van Nevel, L., Vos, B., Hermy, M., & Verheyen, K. (2010). Assessing the effects of initial soil characteristics, machine mass and traffic intensity on forest soil compaction. *Forest Ecology and Management, 260*(10), 1664-1676. https://doi.org/10.1016/j.foreco.2010.08.002

Andrade, R. S., & Stone, L. F. (2009). Índice S como indicador da qualidade física de solos do Cerrado brasileiro. *Revista Brasileira de Engenharia Agrícola e Ambiental*, *13*(4), 382-388. https://doi.org/10.1590/S1415-43662009000400003

Anjos, J .C. R., Almeida, F. P., Ferreira, K., Silva, D. C., Evangelista, A. W. P., Alves Júnior, J., Silva, G. C., & Branquinho, G. (2020). Intensidade e distribuição no espaço-tempo da erosividade da chuva no estado de Goiás e Distrito Federal. *Scientific Electronic Archives*, *13*(10), 1-8. https://doi.org/10.36560/131020201115

Arcoverde, S. N. S., Souza, C. M. A., Suarez, A. H. T., Colman, B. A., & Nagahama, H. J. (2019). Atributos físicos do solo cultivado com cana-de-açúcar em função do preparo e época de amostragem. *Revista de Agricultura Neotropical*, *6*(1), 41-47. https://doi.org/10.32404/rean.v6i1.2761

Arruda, E. M., Almeida, R. F., Domingues, L. A. S., Silva Junior, A. C., Moraes, E. R., Barros, L. R., Sousa, J. L. O., & Lana, R. M. Q. (2016). Soil porosity and density in sugarcane cultivation under different tillage systems. *African Journal of Agricultural Research*, *11*(30), 2689-2696. https://doi.org/10.5897/AJAR2015.10608

Assis, P. C. R., Stone, L. F., Medeiros, J. C., Madari, B. E., Oliveira, J. M., & Wruck, F. J. (2015). Atributos físicos do solo em sistemas de integração lavoura-pecuária-floresta. *Revista Brasileira de Engenharia Agrícola e Ambiental*, *19*(4), 309-316. https://doi.org/10.1590/1807-1929/agriambi.v19n4p309-316

Baquero, J. E., Ralisch, R., Medina, C. C., Tavares Filho, J., & Guimarães, M. F. (2012). Soil physical properties and sugarcane root growth a red oxisol. *Revista Brasileira de Ciência do Solo*, *36*(1), 63-70. https://doi.org/10.1590/S0100-06832012000100007

Barros, R. P., Viegas, P. R. A., Silva, T. L., Souza, R. M., Barbosa, L., Viégas, R. A., Barretto, M. C. V., & Melo, A. S. (2010). Alterações em atributos químicos de solo cultivado com cana-de-açúcar e adição de vinhaça. *Pesquisa Agropecuária Tropical*, *40*(3), 341-346.

Beutler, A. N., Centurion, J. F., Roque, C. G., & Ferraz, M. V. (2005). Densidade relativa ótima de Latossolos Vermelhos para a produção de soja. *Revista Brasileira de Ciência do Solo*, *29*(6), 843-849. https://doi.org/10.1590/S0100-06832005000600002

Bonini, C. S. B., Alves, M. C., & Montanari, R. (2015). Recuperação da estrutura de um Latossolo Vermelho degradado utilizando lodo de esgoto. *Revista Brasileira de Ciências Agrárias*, *10*(1), 34-42. http://dx.doi.org/10.5039/agraria.v10i1a4513

Camilotti, F., Andrioli, I., Dias, F. L. F., Casagrande, A. A., Silva, A. R., Mutton, M. A., & Centurion, J. F. (2005). Efeito prolongado de sistemas de preparo do solo com e sem cultivo de soqueira de cana crua em algumas propriedades físicas do solo. *Engenharia Agrícola*, *25*(1) 189-198. https://doi.org/10.1590/S0100-69162005000100021

Canellas, L. P., Velloso, A. C. X., Marciano, C. R., Ramalho, J. F. G. P., Rumjanek, V. M., Rezende C. E., & Santos, G. A. (2003). Propriedades químicas de um Cambissolo cultivado com cana-de-açúcar, com preservação do palhiço e adição de vinhaça por longo tempo. *Revista Brasileira de Ciência do Solo*, *27*(5), 935-944. https://doi.org/10.1590/S0100-06832003000500018

Castioni, G. A., Cherubin, M. R., Menandro, L. M. S., Sanches, G. M., Bordonal, R. O., Barbosa, L. C., Franco, H. C. J., & Carvalho, J. L. N. (2018). Soil physical quality response to sugarcane straw removal in Brazil: A multi approach assessment. *Soil & Tillage Research*, *184*, 301-309. https://doi.org/10.1016/j.still.2018.08.007

Castro, A. M. C., Santos, K. H., Miglioranza, E., Gomes, C. J. A., & Marchione, M. S. (2013). Avaliação de atributos físicos do solo em diferentes anos de cultivo de cana-de-açúcar. *Revista Agrarian*, *6*(22), 415-422. https://doi.org/10.30612/agrarian.v6i22.1964

Cavalieri, K. M. V., Tormena, C. A., Vidigal Filho, P. S., Gonçalves, A. C.A., & Costa, A. C. S. (2006). Efeitos de sistemas de preparo nas propriedades físicas de um Latossolo Vermelho Distrófico. *Revista Brasileira de Ciência do Solo*, *30*(1), 137-147. https://doi.org/10.1590/S0100-06832006000100014

Ceddia, M. B., Anjos, L. H. C., Lima, E., Ravelli Neto, A., & Silva, L. A. (1999). Sistemas de colheita da cana-de-açúcar e alterações nas propriedades físicas de um solo Podzólico Amarelo no Estado do Espírito Santo. *Pesquisa Agropecuária Brasileira*, *34*(8), 1467-1473. https://doi.org/10.1590/S0100-204X1999000800019

Centurion, J. F., Freddi, O. S., Aratani, R. G., Metzner, A. F. M., Beutler, A. N., & Andrioli, I. (2007). Influência do cultivo da cana-de-açúcar e da mineralogia da fração argila nas propriedades físicas de Latossolos Vermelhos. *Revista Brasileira de Ciência do Solo*, *31*(2), 199-209. https://doi.org/10.1590/S0100-06832007000200002

Cherubin, M. R., Karlen, D. L., Cerri, C. E. P., Franco, A. L. C., Tormena, C. A., Davies, C. A., & Cerri, C. C. (2016). Soil quality indexing strategies for evaluating sugarcane expansion in Brazil. *PLoS ONE*, *11*(3), 1-26. https://doi.org/10.1371/journal.pone.0150860

Dexter, A. R. (1988). advances in characterization of soil structure. *Soil & Tillage Research*, *11*(3-4), 199-238. https://doi.org/10.1016/0167-1987(88)90002-5

Esteban, D. A. A., Souza, Z. M., Tormena, C. A., Lovera, L. H., Lima, E. S., Oliveira, I. N., & Ribeiro, N. P. (2019). Soil compaction, root system and productivity of sugarcane under different row spacing and controlled traffic at harvest. *Soil & Tillage Research*, *187*, 60-71. https://doi.org/10.1016/j.still.2018.11.015

Fagundes, E. A. A., Silva, T. J. A., & Silva, E. M. B. (2014). Desenvolvimento inicial de variedades de cana-de-açúcar em Latossolo submetidas a níveis de compactação do solo. *Revista Brasileira de Engenharia Agrícola e Ambiental*, *18*(2), 188-193. https://doi.org/10.1590/S1415-43662014000200009

Ferreira, D. F. (2014). Sisvar: a guide for its bootstrap procedures in multiple comparisons. *Ciência e Agrotecnologia*, *38*(2), 109-112. https://doi.org/10.1590/S1413-70542014000200001

Freitas, L, Oliveira, I. A., Silva, L. S., Frare, J. C. V., Filla, V. A., & Gomes, R. P. (2017). Indicadores da qualidade química e física do solo sob diferentes sistemas de manejo. *Revista Unimar Ciências*, *26*(1-2), 8-25.

Giachini, C. F., & Ferraz, M. V. (2009). Benefícios da utilização de vinhaça em terras de plantio de cana-de-açúcar - revisão de literatura. *Revista Científica Eletrônica de Agronomia*, *7*(15), 1-5.

Instituto Brasileiro de Geografia e Estatística. (2015). *Manual técnico de pedologia* (3. ed.). IBGE. (Manuais Técnicos em Geociências, n. 4.).

Instituto Brasileiro de Geografia e Estatística. (2018). *Área plantada, área colhida, quantidade produzida, rendimento médio e valor da produção das lavouras temporárias.* IBGE. https://sidra.ibge.gov.br/tabela/1612

Instituto Nacional de Meteorologia. (2021). *Banco de dados meteorológico para ensino e pesquisa*. INMET. https://previsao.inmet.gov.br

IUSS Working Group WRB. (2022). *World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps* (4th ed.). International Union of Soil Sciences.

Kiehl, E. J. (1979). *Manual de edafologia: relações solo-planta* (1. ed.). Agronômica Ceres.

Klein, V. A. (2006). Densidade relativa: um indicador da qualidade física de um Latossolo Vermelho. *Revista de Ciência Agroveterinária*, *5*(1), 26-32.

Kumar, S., Saini, S. K., & Bhatnagar, A. (2012). Effect of subsoiling and preparatory tillage on sugar yield, juice quality and economics of sugarcane (*Saccharum* species hybrid) in sugarcane plant-ratoon cropping system. *Sugar Tech*, *14*(4), 398-404. https://doi.org/10.1007/s12355-012-0170-0

Laurindo, M. C. O., Nóbrega, L. H. P., Pereira, J. O., Melo, D., & Laurindo, E. L. (2009). Atributos físicos do solo e teor de carbono orgânico em sistemas de plantio direto e cultivo mínimo. *Engenharia na Agricultura*, *17*(5), 367-374. https://doi.org/10.13083/reveng.v17i5.163

Lima, C. G. R., Carvalho, M. P., Mello, L. M. M., & Lima, R. C. (2007). Correlação linear e espacial entre a produtividade de forragem, a porosidade total e densidade do solo de Pereira Barreto (SP). *Revista Brasileira de Ciência do Solo*, *31*(6), 1233-1244. https://doi.org/10.1590/S0100-06832007000600002

Lima, V. M. P., Oliveira, G. C., Serafim, M. E., Curi, N., & Evangelista, A. R. (2012). Intervalo hídrico ótimo como indicador de melhoria da qualidade estrutural de Latossolo degradado. *Revista Brasileira de Ciência do Solo*, *36*(1), 71-78. https://doi.org/10.1590/S0100-06832012000100008

Machado, W., Telles, T. S., Tavares Filho, J., Guimarães, M. F, Alves, G. B., & Borges, J. L. B. (2010). Physical properties of a Rhodic Haplustox under two sugarcane harvesting systems. *Revista Brasileira de Ciência do Solo*, *34*(6), 1803-1809. https://doi.org/10.1590/S0100-06832010000600004

Marasca, I., Lemos, S. V., Silva, R. B., Guerra, S. P. S., & Lanças, K. P. (2015). Soil compaction curve of an Oxisol under sugarcane planted after in-row deep tillage. *Revista Brasileira de Ciência do Solo*, *39*(5), 1490-1497. https://doi.org/10.1590/01000683rbcs20140559

Marsili, A., Servadio, P., Pagliai, M., & Vignozzi, N. (1998). Changes of some physical properties of a clay soil following passage of rubber-and metal-tracked tractors. *Soil & Tillage Resarch*, *49*(3), 185-199. https://doi.org/10.1016/S0167-1987(98)00169-X

Matias, S. S. R., Borba, J. A., Ticelli, M., Panosso, A. R., & Camara, F. T. (2009). Atributos físicos de um Latossolo Vermelho submetido a diferentes usos. *Revista Ciência Agronômica*, *40*(3), 331-338.

Medeiros, S. C. L. (2003). *Impactos da agroindústria canavieira sobre o meio ambiente*. III Fórum de Estudos Contábeis.

Moussa-Machraoui, S. B., Errouissi, F., Ben-Hammoeda, M., & Nouira, S. (2010). Comparative effects of conventional and no-tillage management on some soil properties under Mediterranean semi-arid conditions in northwestern Tunisia. *Soil & Tillage Research*, *106*(2), 247-253. https://doi.org/10.1016/j.still.2009.10.009

Mur, M., & Balbuena. R. H. (2014). Compactación de um suelo argiudol típico por tráfico en un sistema de producción de forrajes. *Ciencia del Suelo*, *32*(1), 1-12.

Nicodemo, M. L. F., Borges, W. L. B., & Souza, I. M. D. (2018). Atributos físicos do solo em quatro sistemas de uso da terra em São Carlos, SP. *Revista Brasileira de Ciências Agrárias*, *13*(2), 1-7. https://doi.org/10.5039/agraria.v13i2a5524

Oliveira, G. G., Oliveira, G. C., Silva, E. A., Carducci, C. E., Barbosa, S. M., & Silva, B. M. (2015). Indicadores de qualidade física para Argissolos sob pastagens nas regiões leste e sul de Minas Gerais. *Revista de Ciências Agrárias*, *58*(4), 388-395. https://dx.doi.org/10.4322/rca.2092

Oliveira, I. A., Campos, M. C. C., Soares, M. D. R., Aquino, R. E., Marques Júnior, J., & Nascimento, E. P. (2013). Variabilidade espacial de atributos físicos em um Cambissolo Háplico, sob diferentes usos na região sul do Amazonas. *Revista Brasileira de Ciência do Solo*, *37*(4), 1103-1112. https://doi.org/10.1590/S0100-06832013000400027

Oliveira, V. S., Rolim, M. M., Vasconselos, R. F. B., Costa, Y. D. J., & Pedrosa, E. M. R. (2010). Compactação de um Argissolo Amarelo Distrocoeso submetido a diferentes manejos. *Revista Brasileira de Engenharia Agrícola e Ambiental*, *14*(9), 914-920. https://doi.org/10.1590/S1415-43662010000900002

Pereira, A. A., & Thomaz, E. L. (2014). Estabilidade de agregados em diferentes sistemas de uso e manejo no Município de Reserva-PR. *Revista Brasileira de Geografia Física*, *7*(2), 378-387. https://doi.org/10.26848/rbgf.v7.2.p378-387

Prado, E. A. F., Vitorino, A. C. T., Oliveira, W. H., Espíndola, D. L. P., & Arantes, H. P. (2014). Índice de dispersão de agregados de um Latossolo Vermelho distroférrico cultivado com cana sob aplicação de vinhaça. *Semina: Ciências Agrárias*, *35*(4), 2347-2356. https://doi.org/10.5433/1679-0359.2014v35n4Suplp2347

QGIS. (2021). *QGIS: Geographic Information System (Version 3.16.2)* [Computer software]. QGIS Association. https://www.qgis.org/en/site/

Ramos, H. M. M., Duarte, J. F. B., Simplício, A. A. F., Oliveira, I. M. C., & Feitosa, D. L. (2020). Atributos físico-hídricos de um Neossolo Quartzarênico sob diferentes usos. *Revista Brasileira de Agricultura Irrigada*, *14*(2), 3968-3975. https://doi.org/10.7127/rbai.v14n101147

Reinert, D. J., & Reichert, J. M. (2006). *Propriedades físicas do solo*. Universidade Federal de Santa Maria, Centro de Ciências Rurais.

Reynolds, W. D., Bowman, B. T., Drury, C. F., Tan, C. S., & Lu, X. (2002). Indicators of good soil physical quality: Density and storage parameters. *Geoderma*, *110*(1-2), 131-146. https://doi.org/10.1016/S0016-7061(02)00228-8

Rossetti, K. V., & Centurion, J. F. (2013). Sistemas de manejo e atributos físico-hídricos de um Latossolo Vermelho cultivado com milho. *Revista Brasileira de Engenharia Agrícola e Ambiental*, *17*(5), 472-479. https://doi.org/10.1590/S1415-43662013000500002

Santos, G. G., Marchão, R. L., Silva, E. M., Silveira, P. M., & Becquer, T. (2011). Qualidade física do solo sob sistemas de integração lavoura-pecuária. *Pesquisa Agropecuária Brasileira*, *46*(10), 1339-1348. https://doi.org/10.1590/S0100-204X2011001000030

Santos, H. G., Jacomine, P. K. T., Anjos, L. H. C., Oliveira, V. A., Lumbreras, J. F., Coelho, M. R., Almeida, J. A., Araujo Filho, J. C., Oliveira, J. B., & Cunha, T. J. F. (2018). *Brazilian soil classification system* (5. ed.). Embrapa.

Santos, M. L., Compagnon, A. M., Neto, A. M. P., Arriel, F. H., & Cintra, P. H. M. (2020). Variabilidade espacial das propriedades físicas do solo em primeiro ano de colheita de cana-de-açúcar. *Brazilian Journal of Development*, *6*(5), 27667-27682. https://doi.org/10.34117/bjdv6n5-278

Santos, R. D., Lemos, R. C., Santos, H. G., Ker, J. C., Anjos, L. H. C., & Shimizu, S. H. (2015). *Manual de descrição e coleta de solo no campo* (7. ed.). Sociedade Brasileira de Ciência do Solo.

Severiano, E. C., Oliveira, G. C., Curi, N., & Dias Júnior, M. S. (2009). Potencial de uso e qualidade estrutural de dois solos cultivados com cana-de-açúcar em Goianésia, GO. Revista *Brasileira de Ciência do Solo*, *33*(1), 159-168. https://doi.org/10.1590/S0100-06832009000100017

Silva Junior, C. A., Carvalho, L. A., Centurion, J. F., & Oliveira, E. C. A. (2013). Comportamento da cana-de-açúcar em duas safras e atributos físicos do solo, sob diferentes tipos de preparo. *Bioscience Journal*, *29*, 1489-1500.

Silva, A. A., & Castro, S. S. (2015). Indicadores macro e micromorfológicos da qualidade física de um Latossolo Vermelho cultivado com cana-de-açúcar. *Mercator*, *4*(3), 169-185. https://doi.org/10.4215/RM2015.1403.0010

Silva, A. P., Bono, J. A. M., & Pereira, F. A. R. (2014). Aplicação de vinhaça na cultura da cana-de-açúcar: Efeito no solo e na produtividade de colmos. *Revista Brasileira de Engenharia Agrícola e Ambiental*, *18*(1), 38-43. https://doi.org/10.1590/S1415-43662014000100006

Silva, A. J. N., Cabeda, M. S. V., & Lima, J. F. W. F. (2005). Efeito de sistemas de uso e manejo nas propriedades físico-hidricas de um argissolo amarelo de tabuleiro costeiro. *Revista Brasileira de Ciência do Solo*, *29*(6), 833-842. https://doi.org/10.1590/S0100-06832005000600001

Silva, E. A., Benevenute, P. A. N., & Melo, L. B. B. (2017). Qualidade física de um Latossolo estimada por estudos de curvas de retenção de água, indicadores de fácil determinação e "índice s". *Tecnologia & Ciência Agropecuária*, *11*(4), 49-54.

Silva, E. M., & Azevedo, J. A. (2001). *Período de centrifugação adequado para levantamento da curva de retenção da água em solos do Bioma Cerrado* (Boletim 429 de Pesquisa e Desenvolvimento). Embrapa Cerrados.

Silva, P. L. F., Oliveira, F. P., Borba, J. O. M., Tavares, D. D., Amaral, A. J., & Martins, A. F. (2018). Solos arenosos para Sistemas de integração lavoura-pecuária-floresta em Arez, Rio Grande do Norte. *Revista Verde*, *13*(5), 581-589. http://dx.doi.org/10.18378/rvads.v13i5.6246

Souza, E. B., Rodrigues, M. S., Lima, A. M. N., Cunha, J. C., Silva, K. A., Olszevski, N., & Santos, G. L. M. C. (2019). Índices de compactação na comparação de sistemas de usos do solo com diferentes composições granulométricas. *Ciencia del Suelo*, *37*(1), 173-179.

Tavares, O. C. H., Lima, E., & Zonta, E. (2010). Sugarcane growth and productivity under different tillage and crop systems. *Acta Scientiarum. Agronomy*, *32*(1), 61-68. https://doi.org/10.4025/actasciagron.v32i1.2051

Teixeira, P. C., Donagemma, G. K., Fontana, A., & Teixeira, W. G. (2017). *Manual de métodos de análise de solo* (3. ed.). Embrapa.

Torman, V. B. L., Coster, R., & Riboldi, J. (2012). Normalidade de variáveis: métodos de verificação e comparação de alguns testes não-paramétricos por simulação. *Revista HCPA*, *32*(2), 227-234.

Tormena, C. A., Barbosa, M. C., Costa, A. C. S., & Gonçalves, A. C. A. (2002). Densidade, porosidade e resistência à penetração em Latossolo cultivado sob diferentes sistemas de preparo de solo. *Scientia Agricola*, *59*(4), 795-801. https://doi.org/10.1590/S0103-90162002000400026

Torres, J. L. R., Pereira, M. G., & Fabian, A. J. (2008). Produção de fitomassa por plantas de cobertura e mineralização de seus resíduos em plantio direto. *Pesquisa Agropecuária Brasileira*, *43*(3), 421-428. https://doi.org/10.1590/S0100-204X2008000300018

Vischi Filho, O. J., Souza, Z. M., Silva, R. A., Lima, C. C., Pereira, D. M. G., Lima, M. E., Souza, A. C. M., & Souza, G. S. (2015). Capacidade de suporte de carga de Latossolo Vermelho cultivado com cana-de-açúcar e efeitos da mecanização no solo. *Pesquisa Agropecuária Brasileira*, *50*(1), 322-332. https://doi.org/10.1590/S0100-204X2015000400008

Xavier, A. C. (2020). *Banco de dados meteorológico brasileiro de 1982–2019* [Data set]. University of Texas at Austin. https://utexas.app.box.com/v/Xavier-etal-IJOC-DATA

Yin, J., Deng, C.-B., Wang, X.-F., Chen, G.-L., Mihucz, V. G., Xu, G.-P., & Deng, Q.-C. (2019). Effects of long-term application of vinasse on physicochemical properties, heavy metals content and microbial diversity in sugarcane field soil. *Sugar Tech*, *21*(2), 62- 70. https://doi.org/10.1007/s12355-018-0630-2