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Physical Attributes of Ferralsol in Fertigated Sugarcane Production Environments for Bioethanol in the Midwest of Brazil

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Abstract: Brazil is the world leader in the production and export of sugarcane derivatives, and its center-south region is the main producer. Fertigation with byproducts from bioethanol production can be adopted as a strategy to mitigate the soil physical deterioration resulting from the intensification of mechanized farming practices. The objective of this study was to evaluate the behavior of soil physical attributes under sugarcane cultivation in different crop cycles in fertigated areas in the midwest region of Brazil. The samples were collected in different Ferralsol layers (0.0–0.1, 0.1–0.2, 0.2–0.3, and 0.4–0.5 m) and fertigated crop cycles (first, third, fifth, seventh, and twelfth sugarcane cycles), as well as from native Cerrado vegetation (reference area), and the weight and volume relationships of the soil constituents and total soil were evaluated. Soil physical attributes are affected by sugarcane cultivation cycles and fertigation with vinasse. In the short term (third cycle), the results indicate deterioration of the physical attributes of the soil. However, throughout the cycles of sugarcane culture via fertigation (twelve cycles), the addition of vinasse leads to improvements in physical attributes and soil aggregation, promoting an increase in the longevity of the sugarcane crop. Therefore, the evaluation of the physical attributes of the soil in areas with vinasse application in different sugarcane cultivation cycles should be analyzed in areas of different regions, as this management practice indicates a high potential to increase the longevity of cultivation sugarcane, reducing production costs in the bioenergy sector.

Keywords: bioenergy; Cerrado biome; crop cycles; soil quality; soil structure; vinasse

Citation: Gravina, O.S.; Santos, G.G.; Correchel, V.; Silva, G.C.d.; Medrado, L.d.C.; Flores, R.A.; Mesquita, M.; Severiano, E.d.C. Physical Attributes of Ferralsol in Fertigated Sugarcane Production Environments for Bioethanol in the Midwest of Brazil. *Agronomy* **2021**, *11*, 1641. https://doi.org/10.3390/agronomy11081641

Academic Editors: Antonietta Baiano and Pasquale Massimiliano Falcone

Received: 1 July 2021
Accepted: 13 August 2021
Published: 18 August 2021

1. Introduction

The cultivation of sugarcane (*Saccharum* spp.) is the most important species for the production of sugar and bioenergy in the world, with Brazil being the largest producer in the world, followed by India and China [1,2]. For the 2021/22 harvest alone, Brazilian production is estimated at 628.1 million megagrams (Mg), cultivated 8.4 million hectares, processed 642 million Mg of sugarcane, and produced 27 billion liters of ethanol, 39 million Mg of sugar [3], and 3.8% of the national electricity [4], establishing itself as the largest world power in this agribusiness. The Center-South region is responsible for approximately 92% of Brazil's total sugarcane production [3,4]. Of this amount, the state of Goiás is the second largest producer [3], with an average cane field productivity of 76.4 Mg ha^{-1}.

The importance of these data is based on the relevance of sugarcane as a raw material for renewable and clean energy [5]. These data reinforce the need for efforts for studies aimed at increasing the efficiency of agricultural production of the crop, since it is one of the most promising and sustainable global energy alternatives [6,7].

If, on the one hand, the economic indicators of the sugar-ethanol sector are strong, on the other, the deterioration of the soil structure has been reported as the main negative consequence of the modernization of agricultural systems for sugarcane production [8–15]. This is because soil structural deterioration jeopardizes the growth of the plant's root system [16], negatively affect productivity [11] and longevity of the cane field [17], which reduces the quality and longevity of the cane field [18,19] as a result of soil compaction and erosion processes [20].

In contrast, the use of vinasse in sugarcane plantations (a by-product coming mainly from the sugar-alcohol industry), where for each liter of ethanol produced, an average of 10 to 15 L of vinasse is generated [21–23] and for a long time vinasse was considered a highly polluting environmental liability [24–26], due to the large volume produced and the CO_2 emissions associated with transport in open channels, which can reach the order of 455 g CO_{2eq} per L of ethanol when considering the center-south region of Brazil [27], in addition to the high levels of nutrients [28]. Therefore, its application to the soil is important because it is made of organic matter and thereby improves the structure of the soil. Vinasse also has known benefits in the sugarcane fertilization [29], mainly as a potassium source [5,30,31], being also used as an important source of biogas, which increases the importance of vinasse also as a source of bioenergy [28,32]. Most studies indicate that the application of vinasse increases the organic matter content of soil and minimizes the negative effects of sugarcane culture on soil physical properties [33–38], as well as improving microbial activity [39,40], root distribution [22,41], and sugarcane yield [42].

Therefore, it is believed that the deterioration of the attributes bulk density, total porosity, macroporosity, microporosity, blocked pores, aeration capacity, aggregation and soil organic matter, resulting from continuous mechanized cultivation is mitigated in areas fertigated with vinasse, mainly throughout the cultivation cycles. Thus, the aim of the present study was to evaluate the physical attributes of the soil under cultivation of sugarcane fertigated with vinasse throughout the cultivation cycles in commercial areas in the midwest region of Brazil.

2. Materials and Methods

2.1. Experimental Area Description

The study was conducted in 2018 on soil samples collected from areas of fertigated sugarcane between the 17°57′18.0″ S and 18°0′54.0″ S parallels and the 50°18′54.0″ W and 50°15′18.0″ W meridians in midwest Brazil, in particular the southern part of the state of Goiás (Figure 1) [43,44].

According to the Köppen classification [45], the local climate is Aw (warm climate with summer rains), tropical savanna. In the year under study, the mean air temperature and relative humidity were 23.3 °C and 73.1%, respectively, and the cumulative rainfall was 1287.0 mm. In general, the rainfall data were lower than the mean of the ten previous years (mean temperature of 23.3 °C, mean relative humidity of 71.5%, and mean rainfall of 1572.6 mm for the 2006–2018 historical series (sucroenergetic company data).

The study area is located in the Paraná River Watershed and belongs to the geological convention of the São Bento Group, a sedimentary watershed from the Mesozoic era, more specifically to the Serra Geral Formation, characterized by tholeiitic basalt, dark gray to greenish, with intertraps of fine to very fine sandstone with small to large cross-stratifications [46]. According to the World Reference Base for Soil Resources [47], the soil was described and classified as Ferralsol {Latossolo Vermelho Acriférrico típico, according to the Brazilian Soil Classification System [48]}.

The areas studied, which were converted into commercial sugarcane production fields in 1983, were selected because they are in the same pedological unit, have textural and relief uniformity, and are cultivated with the same sugarcane variety, RB 85-5453. At the time of the study, the selected areas showed variations in the time of the last replanting and number of production cycles (first, third, fifth, seventh, and twelfth sugarcane cultivation cycles, respectively). Their use histories are described in Table 1. As a reference, a native vegetation (NV) area of the Cerrado biome close to the cultivated areas was selected.

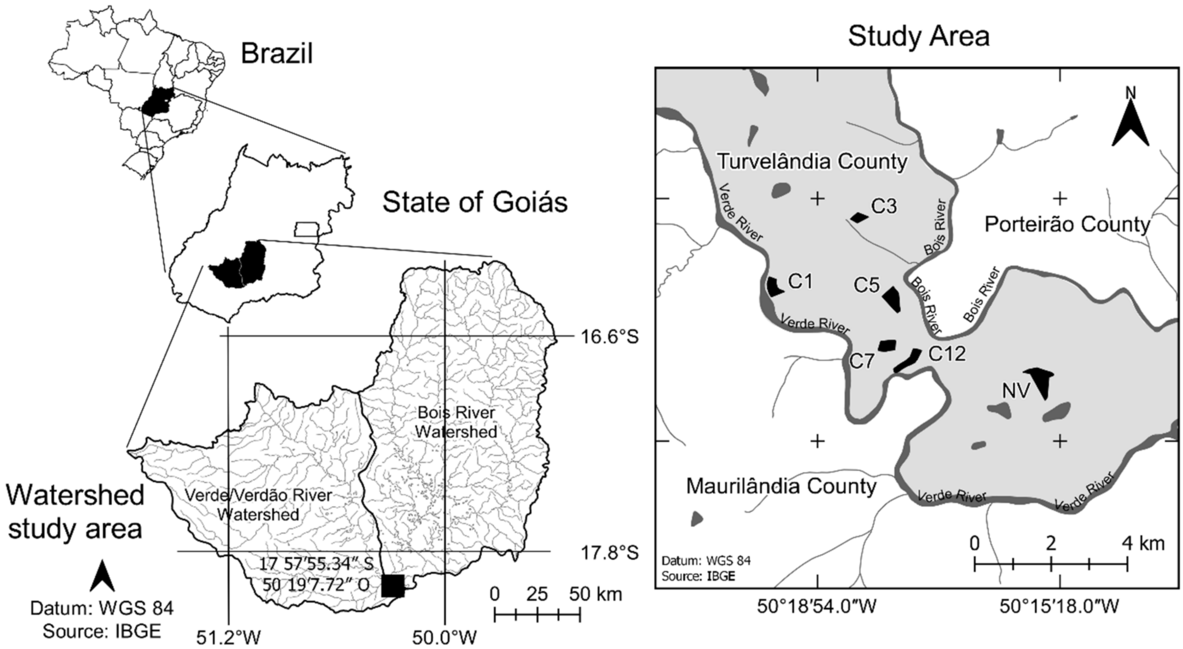

Figure 1. Location of study areas in the Midwest region of Brazil.

Table 1. History of use of the areas under Ferralsol in environments of sugarcane production fertigated with vinasse and native vegetation (NV), in the midwest region of Brazil.

Cycle	Description
C1	Area on the first fertigation cycle of the RB 85-5453 variety in 2018 (plant cane), 11.98 ha, altitude 462 m, at geographical coordinates 17°58′37.54″ S and 50°19′33.73″ W. Previous cultivation of sugarcane fertigated with vinasse from 2009 to 2016. Soybean planting in the summers of 2016–2017. Planting of RB 85-5453 in June 2017, after soybean harvest. Sampling performed before the harvesting operations and yield obtained in the plot of 147.83 Mg ha^{-1} of the RB 85-5453 variety in the 2017/2018 harvest.
C3	Area on the third fertigation cycle (second cut) of RB 85-5453 in 2018, 6.26 ha, altitude 470 m, at geographical coordinates 17°57′33.84″ S and 50°18′17.15″ W. Previous cultivation of sugarcane fertigated with vinasse from 2009 to 2014. Soybean planting in the summers of 2014–2015. Planting of RB 85-5453 in July 2015, after soybean harvest. Productivities of 124.18, 90.10, and 82.95 Mg ha^{-1} of RB 85-5453 in the harvests of 2016/2017, and 2017/2018, respectively.
C5	Area on the fifth fertigation cycle (fourth cut) of the RB 85-5453 variety in 2018, 17.10 ha, altitude 466 m, at geographic coordinates 17°58′48.54″ S and 50°17′46.83″ W. Previous cultivation of sugarcane fertigated with vinasse from 2003 to 2012. Soybean planting in the summers of 2012–2013. Planting of RB 85-5453 in June 2013, after soybean harvest. Productivities of 89.28, 97.09, 77.82, 88.87, and 63.78 Mg ha^{-1} of RB 85-5453 in the harvests of 2014/2015, 2015/2016, 2016/2017, and 2017/2018, respectively.
C7	Area on the seventh fertigation cycle (sixth cut) of the RB 85-5453 variety in 2018, 11.31 ha, altitude 466 m, at geographic coordinates 17°59′29.92″ S and 50°17′52.01″ W. Previous cultivation of sugarcane fertigated with vinasse from 2005 to 2010. Soybean planting in the summers of 2010–2011. Planting of RB 85-5453 in June 2011, after soybean harvest. Productivities of 84.46, 70.73, 103.38, 86.76, 77.90, 70.45, and 50.14 Mg ha^{-1} of RB 85-5453 in the harvests of 2012/2013, 2013/2014, 2014/2015, 2015/2016, 2016/2017, and 2017/2018, respectively.
C12	Area of twelfth fertigation cycle (eleventh cut) of the RB 85-5453 variety in 2018, 11.43 ha, altitude 454 m, at geographic coordinates 17°59′39.94″ S e 50°17′28.19″ W. Soybean planting in the summers of 2005/2006. Planting of RB 85-5453 in July 2006, after soybean harvest. Productivities of 105.63, 94.22, 99.83, 66.10, 88.18, 89.14, 74.71, 80.10, and 51.87 Mg ha^{-1} of RB 85-5453 in the harvests of 2007/2008, 2009/2010, 2011/2012, 2012/2013, 2013/2014, 2014/2015, 2015/2016, 2016/2017, and 2017/2018, respectively.
NV	Area of native vegetation of typical Cerrado (savannah), without human interference, 27.9 ha, altitude 475 m, at geographic coordinates 18°0′3.74″ S and 50°15′34.10″ W.

Before each cultivation, when the sugarcane fields were replanted, the areas received 400 m^3 ha^{-1} of vinasse diluted with wastewater at a 1:1 ratio. Later, the sugarcane ratoons were destroyed with a disc harrow ranging in size from 32 to 36 inches, and 3 Mg ha^{-1} of dolomitic limestone was applied by broadcasting and was incorporated with a moldboard plow, followed by soil loosening with a leveling harrow. The areas were cultivated with soybean (*Glycine max*) in the summer, and after harvest, furrowing for sugarcane planting was performed directly on the legume biomass, with 1.5-m spacing between rows and a furrow size of 0.3 m in depth, 0.5 m in width at the top, and approximately 0.25 m in width at the bottom. The furrows were fertilized with 300 kg ha^{-1} of monoammonium phosphate (MAP) and 7 Mg ha^{-1} of filter cake. Seedlings were distributed manually, and 0.5 L ha^{-1} of fungicide (a.i. pyraclostrobin), 0.25 kg ha^{-1} of insecticide (a.i. fipronil), 0.5 L ha^{-1} of biozyme fertilizer or rooting/budding activator, and 0.2 kg ha^{-1} of sodium molybdate and 2 kg ha^{-1} of zinc sulfate as cover fertilizer were applied. After sugarcane planting, the areas received two more fertigations with 400 m^3 ha^{-1} of vinasse diluted with wastewater, also at a 1:1 ratio.

Harvest of the RB 85-5453 variety from each area, at the end of each cycle, was performed between April and July, mechanically, with a John Deere 3520 harvester together with a tractor and two two-axle haul-outs. After each harvest, the areas received two more fertigations of 400 m^3 ha^{-1} of vinasse diluted with wastewater (in August and September, respectively), also at a 1:1 ratio. The other crop treatments were performed according to the needs of each area and typically involved the application of herbicides via a tractor sprayer (Uniport) and insecticides, foliar fertilizers, and growth regulators via aerial spraying.

2.2. Soil Sampling

To choose the soil sampling sites, 25 points were distributed on a regular grid in each plot. Then, three of these points were randomly selected in each plot and located in the field with a GPS receiver. These points comprised the respective replicates of each cultivation area (Figure 2).

Before harvest, soil samples were collected in each area 0.4 m away from the sugarcane planting row according to Silva et al. [49], in the 0.0–0.1, 0.1–0.2, 0.2–0.3, and 0.4–0.5 m layers. The following were collected: (i) undisturbed samples in stainless-steel cylinders with volume of 100 cm^3 to determine the weight and volume ratios of the soil components; (ii) undisturbed samples (monoliths) in PVC cylinders with an approximate volume of 785 cm^3 for assessing the soil aggregation state; and (iii) deformed samples for soil organic matter and physical soil characterization. Thus, soil samples were collected at three points in each area (C1, C3, C5, C7, C12 and NV), at four depths (consisting of three subsamples per depth), for each of the three types described above.

2.3. Laboratory Evaluations

The deformed samples were sent to the laboratory for determination of gravimetric moisture according to the method described by Teixeira et al. [50]. Then, for the soil organic matter and initial granulometric characterization of the evaluated areas, the deformed samples were air-dried and sieved through a 2-mm mesh to obtain air-dried fine soil (ADFS), according to the method described in Donagema et al. [51]. The soil organic matter and granulometric characterization of the soil is shown in Table 2.

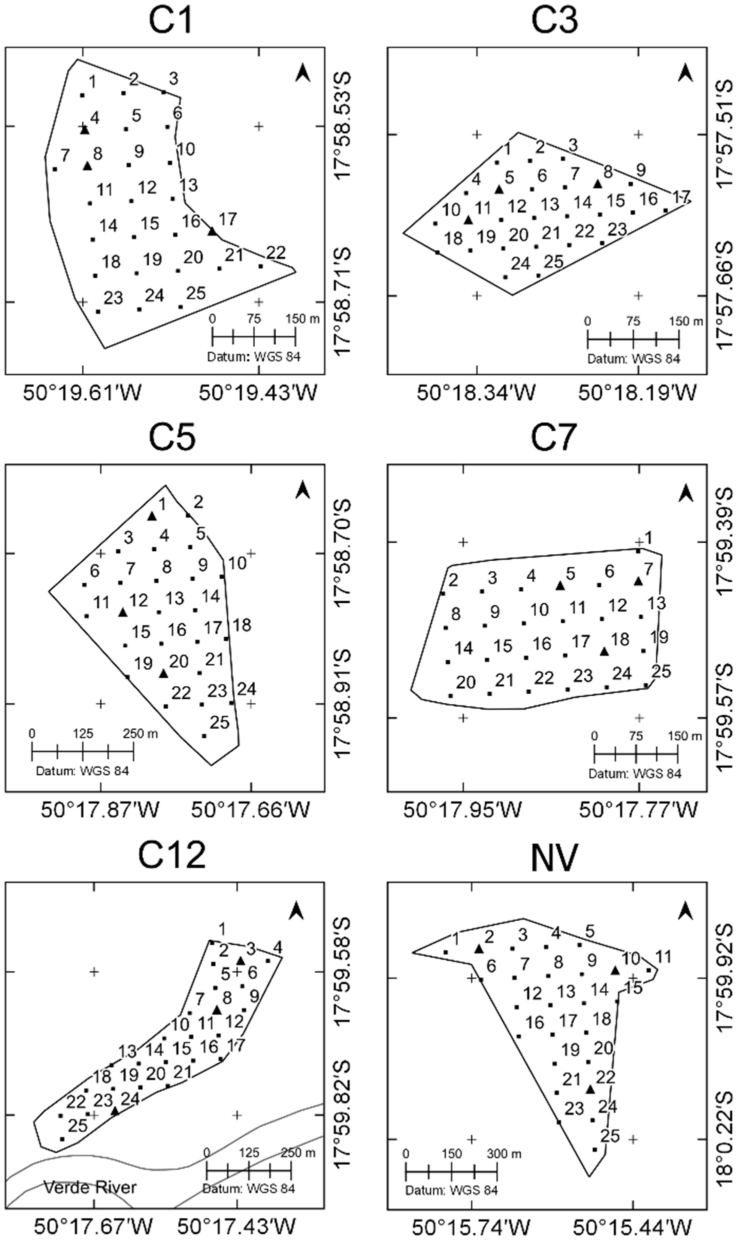

Figure 2. Soil sampling grid on the plots in the study area in the midwest region of Brazil. C1: sugarcane with one year of cultivation; C3: three years of cultivation; C5: five years of cultivation; C7: seven years of cultivation; C12: twelve years of cultivation; and NV: native vegetation.

The undisturbed samples in stainless steel cylinders were prepared in the laboratory by removing excess soil and saturating them by capillarity by filling with water to 2/3 of the height of the cylinders and weighing them. After this procedure, the samples were subjected to matric potentials of −1, −3, and −6 kPa on a tension table and −10, −33, −80, −400, −1000, and −1500 kPa in a Richards extractor, and the respective weights were recorded after drainage had stopped or had become negligible. Lastly, the samples were dried in an oven at 105 °C for 48 h and weighed again Teixeira et al. [50].

The calculations of soil density (Bd), total porosity (Tp), macroporosity (Ma), and microporosity (Mi) were determined according to the procedures described by Donagema et al. [51] and Santos at al. [52]. The attribute blocked pores (Bp) was calculated according to the method described by Libardi [53] and the soil aeration capacity (SAC) using the equation of Reynolds et al. [54].

Table 2. Soil organic matter (SOM) and granulometric characterization of Ferralsol areas in sugarcane production environments and native vegetation (NV), in the midwest region of Brazil.

Cultivation Cycles [(1)]	SOM	Coarse Sand	Fine Sand	Silt	Clay
	g kg^{-1}				
0.0–0.1 m					
C1	37 ± 0.58	120 ± 21.40	158 ± 21.57	323 ± 18.77	399 ± 24.85
C3	35 ± 0.58	152 ± 10.86	199 ± 13.25	230 ± 10.73	419 ± 34.28
C5	27 ± 0.58	85 ± 10.03	200 ± 26.92	184 ± 15.06	531 ± 25.62
C7	26 ± 0.58	55 ± 5.79	140 ± 5.27	239 ± 16.18	566 ± 14.32
C12	37 ± 0.58	162 ± 8.95	216 ± 29.62	244 ±48.64	378 ± 18.55
NV	37 ± 0.58	82 ± 27.68	159 ± 5.76	230 ± 36.86	529 ± 21.54
0.1–0.2 m					
C1	37 ± 0.58	117 ± 22.52	157 ± 19.61	325 ± 8.44	401 ± 33.62
C3	26 ± 0.58	95 ± 12.79	168 ± 20.99	265 ± 17.57	472 ± 37.85
C5	23 ± 0.58	85 ± 8.38	202 ± 32.61	221 ± 32.99	492 ± 33.67
C7	21 ± 0.58	46 ± 2.79	143 ± 6.66	230 ± 27.83	581 ± 23.98
C12	24 ± 0.58	118 ± 13.76	214 ± 33.20	180 ± 20.14	488 ± 30.10
NV	23 ± 0.58	95 ± 0.65	158 ± 5.50	154 ± 1.37	593 ± 7.52
0.2–0.3 m					
C1	26 ± 0.58	71 ± 14.81	124 ± 17.31	296 ± 2.44	509 ± 29.68
C3	37 ± 0.58	98 ± 14.92	150 ± 17.83	245 ± 10.27	507 ± 38.39
C5	23 ± 0.00	83 ± 12.46	202 ± 32.11	204 ± 7.03	511 ± 37.31
C7	18 ± 0.58	45 ± 2.54	143 ± 2.54	238 ± 4.42	574 ± 5.68
C12	26 ± 0.058	110 ± 13.06	206 ± 29.70	205 ± 16.80	479 ± 27.74
NV	14 ± 0.58	68 ± 4.96	150 ± 6.47	174 ± 2.27	608 ± 8.03
0.4–0.5 m					
C1	17 ± 0.88	44 ± 8.24	118 ± 14.29	251 ±22.14	587 ± 3.07
C3	11 ± 0.58	76 ± 4.45	126 ± 4.57	215 ± 18.18	583 ± 9.18
C5	11 ± 0.58	58 ± 8.40	185 ± 31.09	171 ± 34.14	586 ± 34.73
C7	11 ± 0.58	33 ± 4.10	134 ± 5.59	225 ± 10.23	608 ± 12.05
C12	11 ± 0.58	89 ± 15.43	215 ± 31.04	152 ± 7.14	544 ± 53.61
NV	10 ± 0.58	63 ± 6.12	137 ± 1.68	188 ± 4.56	612 ± 8.28

[(1)] C1: sugarcane with one year of cultivation; C3: three years of cultivation; C5: five years of cultivation; C7: seven years of cultivation; and C12: twelve years of cultivation.

Samples in monoliths were used to analyze the stability of wetted aggregates in a Yoder mechanical oscillator [50,55]. The aggregate percentage values were calculated from the results of the laboratory analysis, and the weighted average diameter of the aggregates was calculated as described by Teixeira et al. [50].

2.4. Statistical Analysis

In the results of the soil physical attributes, after the descriptive analysis of the data and once the assumptions of independence, homoscedasticity, and normality of residuals were satisfied [56], the Scott-Knott test was performed at 5% probability (p < 0.05) using Sisvar software, version 5.7 [57]. Graphical were performed using the Microsoft Excel program, version 2013. To apply the principal component analysis (PCA) and create the sample ordering diagram, the Bartlett sphericity test (p < 0.05) was first performed to determine the relationships between the variables (active variables: bulk density “Bd”, total porosity “Tp”, macroporosity “Ma”, microporosity “Mi”, blocked pores “Bp”, soil aeration capacity “SAC”, soil organic matter “SOM”, aggregate class >2.00 mm “Ag1”, between 2.00–1.00 mm “Ag2”, between 1.00–0.50 mm “Ag3”, between 0.50–0.25 mm “Ag4”, between 0.25–0.105 “Ag5”, <0.105 mm “Ag6”, and weighted average diameter “WAD”). After differentiation was observed by this test, the relationships between the soil physical attributes and the centroids of the confidence ellipses for each area were tested using the Xlstat statistical program, version 2016 [58].

3. Results

3.1. Soil Structure

The physical attributes of the soil from the cultivated areas were significantly altered relative to those of the native cerrado vegetation area (NV) (Table 3). Regarding soil density (Bd), the greatest negative effects can be observed in areas C12 and C3 (increases of 27.7 and 23.5%, respectively), while C5, C7, and C1 were less affected areas (increases of 16.8, 19.6 and 20.1%, respectively) in relation to the NV.

Table 3. Average values and mean standard error (±) of the physical attributes of Ferralsol in environments of sugarcane production and native vegetation (NV), in the midwest region of Brazil.

Cultivation Cycles (1)	Bulk Density	Total Porosity	Macroporosity	Microporosity	Blocked Pores	Soil Aeration Capacity
	($g\ cm^{-3}$)	($g\ g^{-1}$)	($g\ g^{-1}$)	($g\ g^{-1}$)	($g\ g^{-1}$)	($g\ g^{-1}$)
C1	1.26 ± 0.030 (b)	0.47 ± 0.022 (b)	0.09 ± 0.010 (c)	0.38 ± 0.014 (a)	0.02 ± 0.003 (c)	0.16 ± 0.013 (c)
C3	1.30 ± 0.014 (a)	0.44 ± 0.008 (c)	0.05 ± 0.006 (d)	0.39 ± 0.007 (a)	0.00 ± 0.001 (d)	0.12 ± 0.013 (c)
C5	1.23 ± 0.027 (b)	0.48 ± 0.017 (b)	0.13 ± 0.019 (b)	0.34 ± 0.008 (b)	0.02 ± 0.008 (c)	0.25 ± 0.033 (b)
C7	1.25 ± 0.025 (b)	0.47 ± 0.016 (b)	0.15 ± 0.015 (b)	0.33 ± 0.004 (b)	0.04 ± 0.007 (b)	0.30 ± 0.022 (b)
C12	1.34 ± 0.027 (a)	0.42 ± 0.015 (c)	0.12 ± 0.011 (b)	0.30 ± 0.012 (c)	0.05 ± 0.004 (b)	0.28 ± 0.023 (b)
NV	1.05 ± 0.017 (c)	0.64 ± 0.014 (a)	0.30 ± 0.017 (a)	0.34 ± 0.005 (b)	0.09 ± 0.009 (a)	0.47 ± 0.017 (a)

(1) C1: sugarcane with one year of cultivation; C3: three years of cultivation; C5: five years of cultivation; C7: seven years of cultivation; and C12: twelve years of cultivation. Different lowercase letters in a column indicate significant differences by the Scott-Knott mean test at 5% significance ($p < 0.05$).

Comparing the soil pore distribution, the highest reductions in total porosity (Tp) values were observed in C12 (35.3%) and C3 (31.2%) and the smallest decreases in C5 (25.9%), C1 (26.2%) and C7 (26.6%). The macroporosity (Ma), responsible for soil aeration, showed values considered very low in C3 (0.05 $g\ g^{-1}$, with a reduction of the order of 82.7% in relation to NV), while lesser intensity decreases were noted in C7 (52.0%), C5 (56.7%) and C12 (61.7%). The microporosity (Mi) of C3 and C1 were superior to all other areas, with increments of the order of 15.0 and 13.1%, respectively, while C12 presented a reduction of 11.5% in relation to NV. Higher proportions of blocked pores (Bp) were observed in C5 and C7 (0.008 and 0.007 $g\ g^{-1}$, respectively), being lower only than those found in NV, while C3 showed 0.001 $g\ g^{-1}$ for this soil attribute. The soil aeration capacity (SAC) showed smaller reductions in areas C7, C12 and C5 (in the order of 35.7, 39.8 and 45.7%) and the most expressive reductions, when compared to NV, were observed in C3 and C1 (74.9 and 65.7%, respectively).

3.2. Soil Aggregation and Organic Matter

With regard to soil aggregation and organic matter, there were notable differences between cultivated areas and NV (Table 4).

Area C12 showed greater aggregation when observing the aggregate class distribution (AG1 = 46.93%) and weighted average diameter (2.7 mm). Among the areas evaluated, the ones with the lowest aggregation, indicated mainly by the highest values for the AG6 aggregate class, were C5 and C3 (AG6 = 17.39% and 18.77%, respectively). SOM was highest in areas C1 and C3 (29.2 and 27.3 $g\ kg^{-1}$, respectively), decreased with cultivation time, and increased again in C12 (24.5 $g\ kg^{-1}$).

Table 4. Average values and mean standard error of the soil aggregate class distribution [(1)], weighted average diameter (WAD), and soil organic matter (SOM) of Ferralsol in environments of sugarcane production and native vegetation (NV), in the midwest region of Brazil.

Sugarcane Area [(2)]	AG1 (%)	AG2 (%)	AG3 (%)	AG4 (%)	AG5 (%)	AG6 (%)	WAD (mm)	SOM (g kg^{-1})
C1	34.21 ± 6.78 (b)	15.77 ± 1.03 (a)	17.41 ± 2.25 (a)	14.72 ± 2.15 (a)	6.48 ± 1.02 (b)	11.40 ± 1.42 (c)	2.15 ± 0.30 (b)	29.2 ± 2.58 (a)
C3	24.46 ± 3.45 (b)	17.02 ± 0.75 (a)	14.76 ± 0.99 (a)	17.00 ± 1.87 (a)	7.99 ± 1.11 (b)	18.77 ± 0.78 (a)	1.68 ± 0.16 (b)	27.3 ± 3.10 (b)
C5	28.70 ± 2.97 (b)	14.51 ± 0.94 (b)	15.25 ± 1.15 (a)	14.97 ± 1.14 (a)	9.17 ± 0.61 (b)	17.39 ± 0.60 (a)	1.85 ± 0.13 (b)	21.0 ± 1.82 (d)
C7	24.41 ± 4.22 (b)	12.57 ± 1.03 (b)	17.31 ± 1.34 (a)	19.09 ± 1.70 (a)	12.81 ± 1.29 (a)	13.81 ± 1.40 (b)	1.64 ± 0.20 (b)	19.0 ± 1.66 (e)
C12	46.93 ± 4.30 (a)	13.93 ± 0.81 (b)	11.74 ± 1.19 (b)	10.55 ± 1.43 (b)	7.53 ± 1.26 (b)	9.33 ± 1.00 (c)	2.70 ± 0.20 (a)	24.5 ± 2.79 (c)
NV	44.31 ± 5.10 (a)	15.47 ± 1.03 (a)	11.37 ± 1.22 (b)	11.24 ± 1.52 (b)	7.68 ± 1.29 (b)	9.93 ± 0.90 (c)	2.59 ± 0.23 (a)	21.0 ± 3.14 (d)

[(1)] Average diameter of the aggregate class: AG1: >2.00 mm; AG2: 1.00–2.00 mm; AG3: 0.50–1.00 mm; AG4: 0.25–0.50 mm; AG5: 0.105–0.250 mm; and AG6: <0.106 mm. [(2)] C1: sugarcane with one year of cultivation; C3: three years of cultivation; C5: five years of cultivation; C7: seven years of cultivation; and C12: twelve years of cultivation. Different lowercase letters in a column indicate significant differences by the Scott-Knott mean test at 5% significance ($p < 0.05$).

3.3. Structure, Aggregation and Organic Matter in Soil Layers

In the detailed analysis of the Bd results by soil layer (Figure 3), the lowest values recorded in the cultivated areas were observed in C1 (1.17 g cm^{-3}) for the 0.0–0.1 m layer and in C5 and C7 (1.13 and 1.15 g cm^{-3}, respectively) in the 0.4–0.5 m layer. No differences were observed in Bd between the other layers of the cultivation areas.

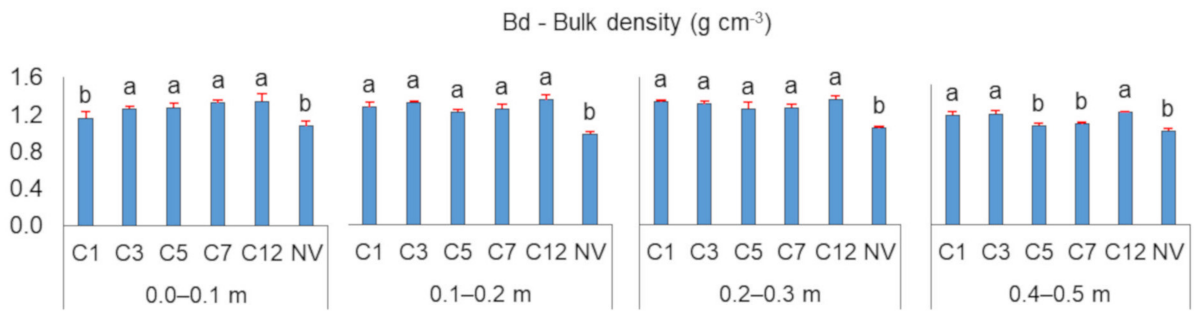

Figure 3. Values of bulk density (Bd) of Ferralsol under different layers and sugarcane production environments in the midwest region of Brazil. C1: sugarcane with one year of cultivation; C3: three years of cultivation; C5: five years of cultivation; C7: seven years of cultivation; C12: twelve years of cultivation; NV: native vegetation. Bars represent mean (±) standard error. Different lowercase letters between the planting times of sugarcane in the same layer indicate significant differences by the Scott-Knott test at a significance level of 5% ($p < 0.05$).

In the detailed evaluation between cultivation cycles and NV by layers, significant effects of land use and management on the physical attributes analyzed at all depths were observed. In the 0.0–0.1 m layer, Tp of C1 (Figure 4a) showed less reduction in values (13.4%), Mi of C1 and C3 (Figure 4c) showed higher values, including NV (23.0 and 20.3%, respectively), and the Bp attribute of C12, C7 and C1 (Figure 4d) showed the smallest negative changes, compared to NV, with reductions in values in the order of 39.1% (C12), 53.1% (C7) and 58.2% (C1). Conversely, when comparing the most expressive (negative) changes between the cultivation cycles and NV, it is noted that Tp was reduced by 34.0% in C12, 32.2% in C7, 29.6% in C5, and 26.2% in C3. These results indicate a negative effect of the traffic of agricultural machinery and equipment on the surface layer, with the increase in sugarcane cultivation cycles. Between cultivation cycles, the Ma attribute (Figure 4b) did not differ for this layer.

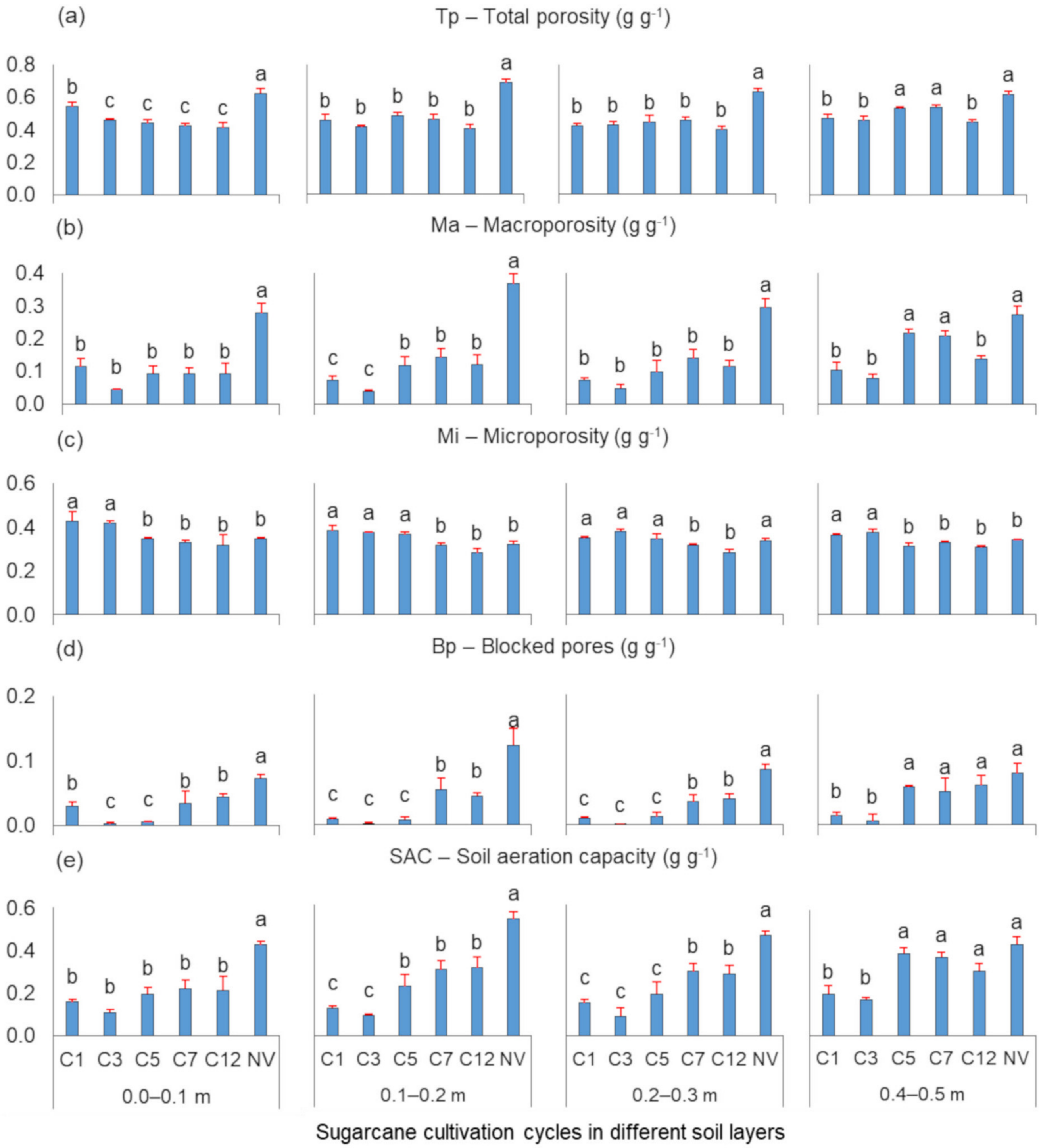

Figure 4. Values of physical soil attributes of Ferralsol in different layers and sugarcane production environments in the midwest region of Brazil. (**a**): Tp—Total porosity; (**b**): Ma—Macroporosity; (**c**): Mi—Microporosity; (**d**): Bp—Blocked pores; (**e**): SAC—Soil aeration capacity. C1: sugarcane with one year of cultivation; C3: three years of cultivation; C5: five years of cultivation; C7: seven years of cultivation; C12: twelve years of cultivation; NV: native vegetation. Bars represent mean (±) standard error. Different lowercase letters between the planting times of sugarcane in the same layer indicate significant differences by the Scott-Knott test at a significance level of 5% ($p < 0.05$).

In the 0.1–0.2 m layer, the Ma attribute (Figure 4b) presented the smallest proportional reductions in values for C7 (61.2%), for C12 (67.3%) and for C5 (67.7%); while Mi of C1, C3 and C5 (Figure 4c) presented higher values, including the NV (19.6, 17.3 and 14.3%, respectively); Bp of C7 and C12 (Figure 4d), with value reductions in the order of 55.5 and 63.7%; and the SAC attribute (Figure 4e) that showed the smallest negative changes, compared to NV, with reductions in values in the order of 41.5% (C12), 43.3% (C7) and 57.6% (C5). For this soil layer, it is noteworthy in proportion, the negative reductions observed for Ma in C3 (89.4%) and C1 (80.1%), for Bp in C3 (98.4%), C5 (93.8%) and C1 (92.7%), and for SAC of C3 (82.4%) and C1 (76.1%), in relation to NV. These expressive and negative results are possibly associated with the effect of mechanized preparation for cultivation in this soil layer.

For the 0.2–0.3 m soil layer, the results show a greater proportion of Mi values (Figure 4c) in relation to NV, for areas C3 (11.9%), C1 (3.1%) and C5 (1.4%); while Bp (Figure 4d) provides the smallest negative changes for C12 (53.0%) and for C7 (58.2%). In addition, when compared to NV, there are smaller negative effects in SAC (Figure 4e) of cycles C7 (35.7%) and C12 (38.1%). Still, it is worth highlighting for this layer, the significant and negative effects detected for the SAC attribute, with reductions of the order of 80.2% in C3 and 67.2% in C1, when compared to NV.

Finally, for the 0.4–0.5 m soil layer, there were positive variations, with emphasis on Tp (Figure 4a) in C7 and C5 (0.54 and 0.53 g g^{-1}, respectively); for Ma (Figure 4b) at C5 and C7 (0.22 and 0.21 g g^{-1}); for Bp (Figure 4d) at C5, C12 and C7 (0.06, 0.06 and 0.05 g g^{-1}); and SAC (Figure 4e) in C5, C7 and C12 (0.40, 0.38 and 0.31 g g^{-1}), whose values, although smaller, did not differ from NV. On the other hand, negative order effects can still be noticed in this layer, with significant reductions in Tp values in C12 (27.4%), C3 (25.7%) and C1 (23.5%); and Bp and SAC in C3 (92.9 and 60.7%) and C1 (82.2 and 54.4%), respectively, when compared to native vegetation.

In general, the soil aggregation results were different between the cultivated areas in a given soil layer, except for the deepest soil (Figure 5), with a predominance of aggregates >2.00 mm (AG1). In the topsoil layer, ranging from 0.0–0.1 m in depth, C12 (Figure 5a,f) stood out, with 56.75% of the aggregates being larger than 2.00 mm (AG1) and 8.44% of aggregates smaller than 0.106 mm (AG6). In the 0.1–0.2 m layer, only AG6 showed differentiation between the cultivated areas (Figure 5f), with areas C12 (9.39%), C1 (10.59%), and C7 (11.48%) having the lowest percentages of this aggregate class. In the 0.2–0.3 m layer (Figure 5e,f), areas C1 and C12 showed the lowest percentages of microaggregates (AG5 + AG6 = 13.89 and 17.45%, respectively), which are aggregates smaller than 0.25 mm, while C7, C5, and C3 were the areas where the highest abundance of microaggregates was observed (AG5 + AG6 = 32.31, 29.17, and 29.05%, respectively). In the last soil layer evaluated, there was no differentiation in the aggregate classes between the cultivated areas or relative to the NV (Figure 5a–f).

The weighted average diameter (WAD), an index of the stability of soil aggregates, showed differences between areas only in the topsoil layer, and it did not vary in the other layers evaluated (Figure 6). Specifically, the C12 area in the 0.0–0.1 m layer differed from the others, with a WAD value of 3.14 mm, close to that of the NV area (3.69 mm).

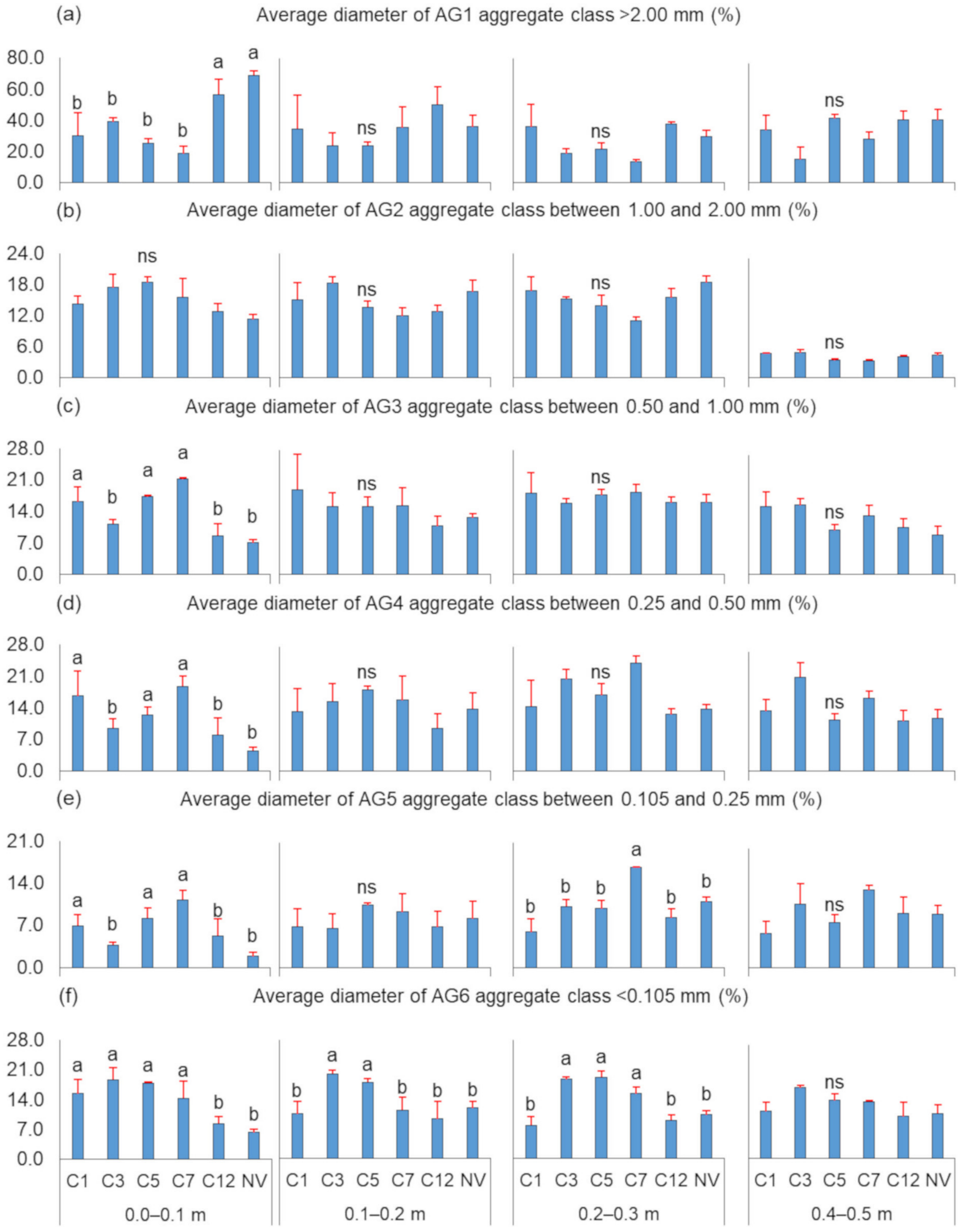

Figure 5. Aggregate classes of Ferralsol in different layers and sugarcane production environments in the midwest region of Brazil. (**a**): Average diameter of AG1 aggregate class >2.00 mm; (**b**): Average diameter of AG2 aggregate class between 1.00 and 2.00 mm; (**c**): Average diameter of AG3 aggregate class between 0.50 and 1.00 mm; (**d**): Average diameter of AG4 aggregate class between 0.25 and 0.50 mm; (**e**): Average diameter of AG5 aggregate class between 0.105 and 0.25 mm; (**f**): Average diameter of AG6 aggregate class <0.105 mm. C1: sugarcane with one year of cultivation; C3: three years of cultivation; C5: five years of cultivation; C7: seven years of cultivation; C12: twelve years of cultivation; NV: native vegetation. Bars represent mean (±) standard error. Different lowercase letters between the planting times of sugarcane in the same layer indicate significant differences by the Scott-Knott test at a significance level of 5% ($p < 0.05$). ns: not significant.

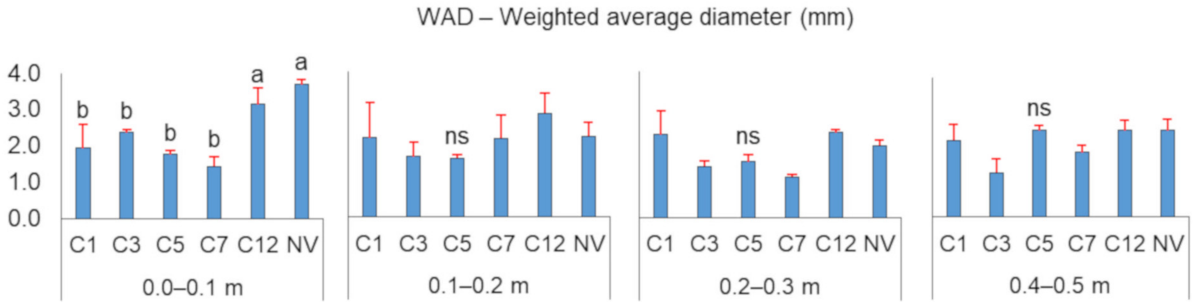

Figure 6. Weighted average diameter of Ferralsol in different layers and sugarcane production environments in the midwest region of Brazil. C1: sugarcane with one year of cultivation; C3: three years of cultivation; C5: five years of cultivation; C7: seven years of cultivation; C12: twelve years of cultivation; NV: native vegetation. Bars represent mean (±) standard error. Different lowercase letters between the planting times of sugarcane in the same layer indicate significant differences by the Scott-Knott test at a significance level of 5% ($p < 0.05$). ns: not significant.

Regarding the soil organic matter (SOM) content, there was variation between the cultivated areas and between the soil layers evaluated (Figure 7). The following areas had the highest SOM contents in the different layers: 0.0–0.1 m: C1 and C12 (37.00 g kg^{-1} in both, similar to NV); 0.1–0.2 m 0.4–0.5 m: only C1 (37.00 and 16.66 g kg^{-1}, respectively); and 0.2–0.3 m: only C3 (37.00 g kg^{-1}). Among all cultivated areas, C7 showed the lowest amount of SOM in all soil layers evaluated (26.00, 21.00, 18.00, and 11.00 g kg^{-1}, respectively).

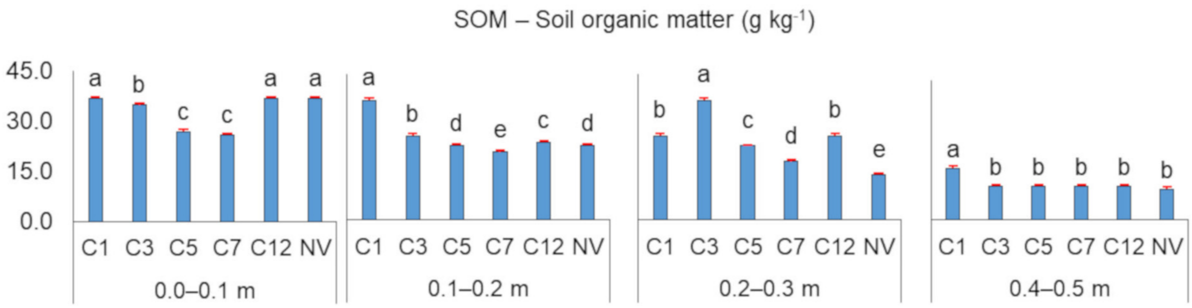

Figure 7. Soil organic matter content of Ferralsol in different layers and sugarcane production environments in the midwest region of Brazil. C1: sugarcane with one year of cultivation; C3: three years of cultivation; C5: five years of cultivation; C7: seven years of cultivation; C12: twelve years of cultivation; NV: native vegetation. Bars represent mean (±) standard error. Different lowercase letters between the planting times of sugarcane in the same layer indicate significant differences by the Scott-Knott test at a significance level of 5% ($p < 0.05$).

3.4. Principal Component Analysis

In the PCA (Figure 8a), the soil physical attributes were grouped as a function of the sugarcane cultivation time, and Bartlett's sphericity test showed significance ($p < 0.0001$). Axis 1 explained 45.03% of the variability in the data and axis 2 explained 24.17%, totaling 69.20% of the total variability in the data.

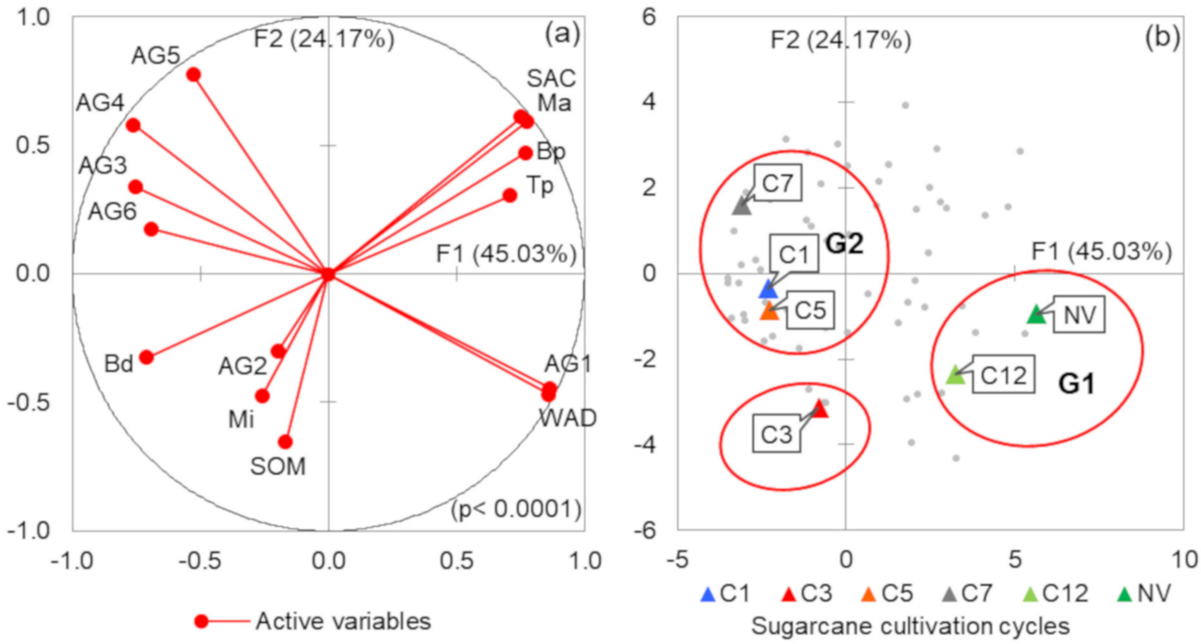

Figure 8. Principal component analysis (**a**) and biplot for grouping areas (**b**) of the physical attributes of Ferralsol under different cultivation times in sugarcane production environments in the midwest region of Brazil. Active variables: Bd: bulk density; Tp: total porosity; Ma: macroporosity; Mi: microporosity; Bp: blocked pores; SAC: soil aeration capacity; AG1: aggregate class > 2.00 mm; AG2: class of aggregates between 1.00 and 2.00 mm; AG3: class of aggregates between 0.50 and 1.00 mm; AG4: class of aggregates between 0.25 and 0.50 mm; AG5: class of aggregates between 0.105 and 0.25 mm; AG6: aggregate class < 0.105 mm; WAD: weighted average diameter; SOM: soil organic matter. C1: sugarcane with one cycle of cultivation, C3: three cycles of cultivation, C5: five cycles of cultivation, C7: seven cycles of cultivation, C12: twelve cycles of cultivation; NV: native vegetation.

Axis 1 was mainly influenced by the physical attributes AG1, WAD, Ma, Bp, SAC, and Tp, with factor loadings of 0.867, 0.862, 0.774, 0.772, 0.753, and 0.710, respectively, and the attributes AG4, AG3, Bd, and AG6, with factor loadings of 0.761, −0.753, −0.709, and −0.694. In turn, axis 2 was influenced by AG5, with factor loadings of 0.776, and SOM, with factor loading −0.654. Figure 8b shows the separation of the areas as a function of the confidence ellipses of the biplot, confirming the results shown in Tables 3 and 4, with greater proximity between area C12 and NV.

4. Discussion

Changes in most physical attributes related to soil weight and volume in relation to soil under NV (Table 3) are due to textural differences between plots and mechanized operations that cause soil structure deterioration [15,42,59,60], as well as the action of vinasse, particularly in areas with long-term additions of this byproduct via fertigation. The increase in Bd and reductions in Tp and Ma in the soil of cultivated areas compared to NV have been described in numerous studies [9,61,62], being in agreement with the results of this study.

The soil tillage practices and the apparent cumulative effect of traffic on the soil physical properties, particularly during the sugarcane harvesting operations in the first crop cycles [14], may have contributed to the higher Bd and lower Tp recorded in C3, similar to C12 (Table 3). However, this latter area had the lowest clay content, which is related to higher Bd values [63], and had Ma values higher than C3 (and higher than 10%, a range considered limiting to this attribute) [17]. This relationship can also be visualized through PCA (Figure 8).

In the topsoil layer (0.0–0.1 m), there was an increase in Bd (C1: 1.17 g cm^{-3}; C3: 1.27 g cm^{-3}; C5: 1.28 g cm^{-3}; C7: 1.33 g cm^{-3}; C12: 1.35 g cm^{-3}) and reduction in Tp

(0.54 g g^{-1}, 0.46 g g^{-1}, 0.44 g g^{-1}, 0.42 g g^{-1}, 0.41 g g^{-1}, respectively) with cultivation time, and the Bd of C1 was comparable to that of NV (Figure 4). However, this trend was not observed in the other layers, perhaps due to the more immediate effect on the topsoil layer. C3 showed a similar pattern of Bd and Tp as C12 did (Table 3). Although C3 is the second most recently replanted area, the results of the negative structural changes observed in the physical attributes of the soil represent the natural reorganization of the granulometric size particles, dispersed during the initial soil preparation operations, added to the impacts caused by the first operations harvest, which reflect greater deterioration capacity, as described in the literature [8,10,11,14]. In addition, in C1, C5, and C7 the values of Bd and Tp were similar (Table 3). However, as detailed in Figures 3 and 4, C1 obtained better results for these physical attributes in the 0.0–0.1 m layer and C5 and C7 in the 0.4–0.5 m layer.

In the case of C1, the short time elapsed between the soil tillage operations and the sampling explains the reduced soil-physical attributes degradation found in the topsoil in this area, as explained in a study [64] of a similar nature, unlike the pattern observed in C3. However, over time, fertigation with sugarcane vinasse promoted structural improvements in the soil, quantified both by the reduction in Bd at depth in C5 and C7 and by the increases in mean Ma and SAC (Figures 4 and 6; Table 3), in line with literature [38,49,65–67]. Finally, we emphasize that the Bd values found are compatible with those described by Cavalieri et al. [65], Centurion et al. [9] and Souza et al. [68], who recorded 1.32, 1.53, 1.56 g cm^{-3}, and, respectively, up to 0.2 m depth, for the same soil class and texture.

In general, starting in the fifth cycle, the values of Ma recorded were higher and were above the critical limit [9,17], as were those of SAC, while the Mi values were lower (Table 3; Figure 4). In a study [49], higher macropore values occurred in fertigated soils and were attributed to the better development of the root system due to the application of vinasse. Here, we also emphasize the organic nature of this byproduct as a microbiological activator in the soil, which in turn has a direct effect on soil structural improvement [36–38]. Furthermore, due to its physicochemical composition, vinasse also behaves as a cementing agent [69] and aggregant of individual particles into larger granules [70]. In addition, Souza et al. [71] found an increase in soil macropores with the increase in plant cover on the soil surface resulting from the accumulation of straw from successive harvests over the years. Many studies have pointed out that the accumulation of sugarcane straw on the soil surface [72] tends to minimize the negative effects on the physical properties of the soil [61,73–75], mainly due to the negative effect caused by mechanical harvesting on the surface layer. These phenomena may have contributed to the results obtained.

In contrast to the Bd and Tp results, C12 showed better soil structure than the other cultivated areas, with a higher percentage of AG1 (aggregates > 2.00 mm) and lower percentage of AG5 and AG6 (aggregates < 0.25 mm), in addition to the highest WAD recorded (Table 4; Figures 5 and 6).

The WAD is an index of aggregate stability [76]. Several authors have found higher WAD in areas under natural vegetation than cultivated areas [9,77,78] which is attributed to the permanent presence of organic residues in the soil and the action of microorganisms in the formation of aggregate cementing and stabilizing compounds [77].

The structural improvement in the topsoil layer of C12 (Figures 4–6) may be related to the higher SOM value, lower soil tillage, and addition of straw to the soil may stop the decline in the structural quality of cultivated soils and promote the recovery of already degraded soils [79]. Along the same lines, Cavalcanti et al. [80] found that years of successive sugarcane cultivation could promote improvements in water-stable aggregates, among other aspects.

Moreover, the roots of perennial grasses have a positive effect on soil aggregation. Added to this is the longer vinasse application time [81]. In this sense, the application of vinasse can increase the proportion of water-stable macroaggregates (>2.00 mm) and, consequently, increase WAD [36,38,41].

The PCA used to group the data related to the physical attributes as a function of sugarcane cultivation time (Figure 8a) clearly showed negative relationships between Bd and the Ma, SAC, Bp, and Tp attributes, confirming that as Bd decreases, the values of the soil porosity–related attributes increase. Similarly, as the AG1 and WAD values increased, there were decreases in the AG4, AG5, AG3, and AG6 aggregate classes. These findings are consistent with the literature, considering that a reduction in pore space accompanied by increased soil density [12,49,62,66,68,82] and a reduction in microaggregation accompanied by increased macroaggregation in this type of soil are expected results [36,38].

Figure 8b clearly shows the separation of area C3 from the others, where the greatest negative changes were observed in the soil physical attributes and aggregation due to the greater impact of mechanized harvesting and recent soil tillage. Conversely, area C12 (group G1) was the one that most closely resembled the NV area (reference area), showing the positive cumulative effect of vinasse application over the years on the physical recovery of the soil, confirming the results shown in Tables 3 and 4.

5. Conclusions

Soil physical attributes are affected by sugarcane cultivation cycles and fertigation with vinasse. In the short term (third cycle), the results indicate deterioration of the physical attributes of the soil. However, throughout the cycles of sugarcane culture via fertigation (twelve cycles), the addition of vinasse leads to improvements in physical attributes and soil aggregation, promoting an increase in the longevity of the sugarcane crop. Therefore, the evaluation of the physical attributes of the soil in areas with vinasse application in different sugarcane cultivation cycles should be analyzed in areas of different regions, as this management practice indicates a high potential to increase the longevity of cultivation sugarcane, reducing production costs in the bioenergy sector.

Author Contributions: All authors equally contributed to the conceptualization, original draft preparation, and review and editing of this manuscript. All authors have read and agreed with the manuscript version.

Funding: Goiás State Research Support Foundation for the scholarship (Public Call nº 3/2017) and for the funding the project (Agronomic variables and improvement of the sugarcane production process in the state of Goiás, under process nº 201610267001488); Goiano Federal Institute for financial support; and Vale do Verdão Refinery for logistical support in field activities. The authors would like to thank the funding provided by the National Council for Science and Technology (CNPq), and RAF would like to thank CNPq for the PQ funds process number 306329/2019-0.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: No conflict of interest have been declared.

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