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Different managements in conventional sugarcane reform in sandy soils: effects on physical properties and soil organic carbon

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ABSTRACT: Sugarcane culture in Brazil has expanded the planting area to degraded pastures and sandy soils. Sugarcane field reform is carried out after five or more harvest cycles, with conventional tillage, followed by planting sugarcane, or growing soybeans or a cover crop. This study aimed to analyze the effects of these different managements in the conventional sugarcane reform on the physical properties and organic carbon in an *Argissolo Vermelho distrófico arênico* (sandy Ultisol), located at latitude 21° 13’ 40” south, longitude 50° 52’ 06” west, and altitude of 449 m. In each management study, areas of 10 ha were delimited in which 36 months after the renovation period, during the 3rd crop cycle, soil samples were collected in eight trenches measuring 1.0 × 1.0 × 0.5 m, 30 m apart between the crop rows and 0.25 m from the planting furrow, to analyze: the stability index of aggregates in the layers of 0.00-0.10 and 0.10-0.20 m and density and porosity (total, macro, and microporosity) of the soil in addition to organic carbon, in the layers of 0.00-0.10, 0.10-0.20, 0.20-0.30 and 0.30-0.40 m. The results allowed us to conclude that the tillage+sugarcane and tillage+soy managements negatively affected the physical properties compared to the tillage+cover crop management, whose use of *Crotalaria spectabilis* provided higher Pt, higher Ma, and Mi, higher AS. Furthermore, the increase in carbon contents was low, with small variations between treatments.

Keywords: cover crop, Crotalaria, soil physical quality.

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INTRODUCTION

Sugarcane crop had an expansion of the planting area between 2005 and 2020 in Brazil, which increased the production in degraded pastures and sandy soils areas (70 % of sand and less than 15 % of clay) (Oliveira et al., 2019; Cherubin et al., 2021). Sand soils cover 8 % of the Brazilian territory (≈8,561,000 million hectares) and are considered soils of low agricultural potential compared to clayey soils (Donagema et al., 2016). These soils have low CEC, limited availability of N, P, and S, high nutrient loss by leaching, low water storage and accumulation of organic matter, in addition to poor aggregation, low resilience, and resistance to degradation due to its low reactivity (Reichert et al., 2018; Yost and Hartemink, 2019).

Given the economic viability of sugarcane, major soil interventions only occur after five or more harvest cycles. The operations, called conventional tillage, comprise soil turning and subsoilers, and aim to reduce soil compaction, by promoting cracks and reducing aggregates, with increased aeration and water infiltration into the soil (Coleti, 2008; Moraes et al., 2021). According to Bolonhezi and Gonçalves (2015), after conventional preparation, three management possibilities during sugarcane reform can be used, depending on the costs involved and the time available for their execution: sugarcane planting, the cultivation of soybeans or a cover crop (Rabot et al., 2018; Moraes et al., 2021).

Any of these management possibilities requires investment in edaphic and vegetative soil management and conservation practices in order not to compromise the physical properties (Huang and Hartemink, 2020), especially porosity, so as not to favor particle drag (erosion) (Yost and Hartemink, 2019) besides keeping of favorable aspects for rooting of crops.

Therefore, of the three managements considered for sandy soils after the reform period: planting sugarcane (allows for agility in harvesting the crop for the next harvest), soybean cultivation (adding financial gains to the sugar-energy chain), or cover crop (promoting an increase in organic matter in the soil and adds a series of benefits to the soil), which provides better porosity? We believe that it will be confirmed that the management of soil preparation + cover crop will cause less damage to the physical properties of these sandy soils, even if large increases in carbon contents are not observed due to the time of experimentation. Our objective was to analyze the effects of different management in the conventional sugarcane reform on sandy soils' physical properties and organic carbon.

MATERIALS AND METHODS

Study region and soil

Our study was carried out under an *Argissolo Vermelho distrófico arênico* (sandy Ultisol), located in the northwest region of the state of São Paulo, in the municipality of Valparaíso (latitude 21° 13' 40" south, longitude 50° 52' 06" west and altitude of 449 m). The biome of the region is of the cerrado type. The climate, according to Köppen classification system, is Aw (tropical humid with dry winter), with maximum, average and minimum annual temperature, respectively, of 31, 24 and 18 °C and annual precipitation volume of 1200 to 1500 mm, with the coldest dry month, rainfall of less than 60 mm (Agritempo, 2019).

Study areas

Three sugarcane production areas were selected with a history of use and occupation by pastures from 1970 to 2000. These areas were submitted to five harvest cycles to be later reformed. From 2000 to 2010, the harvest was carried out under burnt cane and from 2011 under raw cane. The three adjacent study areas were divided according to the management system used during the renovation period, that is, conventional tillage + sugarcane, conventional tillage + cover crop (*Crotalaria spectabilis*), and conventional tillage + soy (Figura 1). Conventional tillage, common in the three study areas and carried out during the renovation period, is characterized by the operations of chemical desiccation of the ratoon and heavy and intermediate harrowing, subsoiling, and leveling harrowing.

Soil attributes of the surveyed areas are shown in table 1. Application of correctives (limestone and gypsum) was carried out simultaneously with the soil turning operations. Then, the areas were managed by the different management systems. In the tillage + sugarcane management system, the chemical desiccation of the ratoon took place between October/2015 and November/2015, with the culture remaining desiccated until March/2016 when the area was subjected to conventional preparation and the planting of the ratoon was carried out culture underexposed soil, with 1.50 m spacing between furrows.

Figure 1. Areas involved in the research: (a) conventional tillage + sugarcane; (b) conventional tillage + soybean; (c) conventional tillage + cover crop (*Crotalaria spectabilis*).

Table 1. Characteristics of *Argissolo Vermelho distrófico arênico* (sandy Ultisol) in the studied areas

Layer	Sand	Silt	Clay	CTC
m		$g\ kg^{-1}$		$cmol_c\ dm^{-3}$
		Conventional tillage + sugarcane[(1)]		
0.00-0.10	690	30	280	8.16
0.10-0.20	670	80	250	7.96
0.20-0.30	670	110	220	6.95
0.30-0.40	650	50	300	6.53
		Conventional tillage + cover crop (*Crotalaria spectabilis*)		
0.00-0.10	790	120	100	7.63
0.10-0.20	800	110	90	6.64
0.20-0.30	780	120	110	6.44
0.30-0.40	770	110	130	6.58
		Conventional tillage + soy		
0.00-0.10	810	100	90	6.67
0.10-0.20	800	90	120	6.05
0.20-0.30	800	110	100	5.19
0.30-0.40	770	90	140	5.13

[(1)] Determinations carried out at the Soil Genesis Laboratory/ESALQ/USP/Brazil). Soil mineralogy: quartz, kaolinite, goethite, gibbsite, and hematite.

About the management system tillage + cover crop (Crotalaria spectabilis), shortly after the sugarcane harvest, in September/2015, the area was submitted to conventional tillage in October/2015, and the sowing of Crotalaria spectabilis was carried out at haul, and the seeds incorporated with a leveling harrow. This cultivation lasted until March 2019, when the sugarcane no-tillage operation was carried out on the green mass of the cover crop, with a spacing between furrows of 1.50 m (Coleti, 2008).

In the management system tillage + soy, the area was managed in a similar way to the area with a cover crop but cultivated with soybean ("cultivar Potência - Brasmax®") from October/2015 to March/2016.

Management of areas during crop cycles

Four months after harvest, all areas were submitted to subsoiling operation (with subsoiler/cultivator, with two subsoiler rods with winged tips) together with the application or not of correctives, depending on the area. At this time, fertilizers and vinasse were applied.

Soil sampling

Soil samples were collected 36 months after the renovation period, during the 3rd crop cycle, in eight trenches measuring 1.0 × 1.0 × 0.5 m, 30 m apart (a total of 24 trenches), between the crop rows and at 0. 25 m from the planting furrow, in delimited areas of 10 ha.

Undisturbed samples (four samples per treatment and per layer) were collected to evaluate the aggregate stability index in the layers of 0.00-0.10 and 0.10-0.20 m and undisturbed samples for analysis of density and porosity (total, macro, and microporosity) of the soil in addition to organic carbon, in the layers of 0.00-0.10, 0.10-0.20, 0.20-0.30, and 0.30-0.40 m.

Methodology used to analyze the samples collected

Bulk density and porosity (total, macro, and microporosity) were determined in undisturbed samples, according to the methodologies described by Donagema et al. (2011). The aggregate stability index for these very sandy soils was determined in the field according to the following procedure: undisturbed samples were placed in a set of sieves (2, 1, 0.50 and 0.250 mm opening) and shaken with light horizontal movements for 1 min; then, the aggregates from each sieve were placed in plastic bags lined with paper towels, taken to the laboratory and placed in an oven for 24 h, weighed, and then the aggregate stability index (EAI) was calculated by the equation 1.

$$AS\,(\%) = \left\{\frac{\left[Xi>25 - \left(MS_{dry} \times \left(\%sand/100\right)\right)\right]}{MS_{dry}}\right\} \times 100 \qquad \text{Eq. 1}$$

in which: Xi>25: mass of soil retained in sieves with opening >0.25 (mm); MS_{dry}: total dry soil mass of each sample (g).

To determine organic carbon (OC), we used the methodology of Walkley and Black (1934) (WB), described by Fontana and Campos (2017). This method has good accuracy and oxidizes the most reactive MO fractions in the soil (Tedesco et al., 1995). This is in agreement with Rheinheimer et al. (2008), who found that in soils under native vegetation and no-till, even with different textures, the WB method was the most accurate method to determine higher levels of TOC in the soil due to the lower coefficients of variation between the samples. In addition, Sato et al. (2014) concluded that the WB method, together with the colorimetric methods, presents similar efficiency in the determination of soil C, with results close to the reference method (elemental analysis).

Statistical analysis

Initially, the data from each evaluated layer were submitted to normality and homoscedasticity tests, using the Shapiro Wilk and Bartlét tests, respectively. Analysis of variance was performed using the F Test ($p<0.05$) in a completely randomized design (DIC), comparing the means using the Scott Knott test ($p<0.05$). Correlation tests were performed between OC contents and soil physical properties through Pearson's linear correlation coefficient ($p<0.05$), and data from the four soil layers and the three management systems evaluated, were submitted to multivariate analyses: cluster and principal components analysis. All statistical procedures were performed in the R software-R Core Team 2021.

RESULTS

Analyses of sandy soil samples collected 36 months after the renovation period (Table 2) show the influence of the studied management.

The management's tillage + sugarcane and tillage+cover crop presented equality of density in the layer of 0.00-0.10 m. However, when we observe the depths 0.00 and 0.40 m, it is verified that the tillage + cover crop management presented the lowest density values and the highest porosity values (total, macro, and microporosity), while the tillage + sugarcane management and tillage + soy the highest density values and the lowest porosity values (total, macro, and microporosity), at the same depth (Figure 2).

As for the aggregate stability index (AS), the lowest values occurred for the tillage + sugarcane system, while the highest values occurred for the systems with tillage + cover crop and tillage + soy (Figure 3).

Regarding organic carbon, the tillage + soy system caused the lowest values at layer of 0.00-0.40 m. The systems, tillage + cover crop and tillage + sugarcane, were similar at the layers of 0.00-0.10 and 0.20-0.30 m, but different at the layers 0.10-0.20 and 0.30-0.40 m (Figure 4).

Correlations between OC contents and physical properties showed that the increase in OC concentration causes an improvement in the physical conditions of the soil. This is demonstrated by the negative correlations with BD and positive correlations with PT, Ma, and Mi (table 3). Only for the AS, there was no significant correlation (table 3).

Multivariate analyzes indicated the formation of two groups: one with the tillage + cover crop system, and the other with the tillage + sugarcane and tillage + soy systems (Figure 5a). This is due to the more favorable conditions (higher correlation between this system and the variables Pt, Ma, and Mi) of the physical properties

Table 2. Summary of analysis of variances for organic carbon and soil physical properties, evaluated after 36 months

Layer	OC		AS		BD		PT		Ma		Mi	
	p-value	CV	p-value	CV	p-value	CV	p-value	CV	p-value	CV	p-value	CV
m		%		%		%		%		%		%
0.00-0.10	0.017	17.2	<0.0001	2.3	0.015	3.6	<0.0001	6.1	<0.0001	20.4	<0.0001	8.4
0.10-0.20	0.001	24.3	<0.0001	2.3	<0.0001	2.4	<0.0001	6.4	0.041	28.4	<0.0001	5.3
0.20-0.30	0.001	16.3	-	-	0.002	3.9	<0.0001	5.4	0.000	20.2	<0.0001	5.4
0.30-0.40	<0.0001	19.6	-	-	<0.0001	2.6	<0.0001	4.6	<0.0001	13.7	<0.0001	4.5

OC: organic carbon; AS: aggregate stability index; BD: bulk density; PT: total porosity; Ma: macroporosity, Mi: microporosity, CV: coefficient of variation.

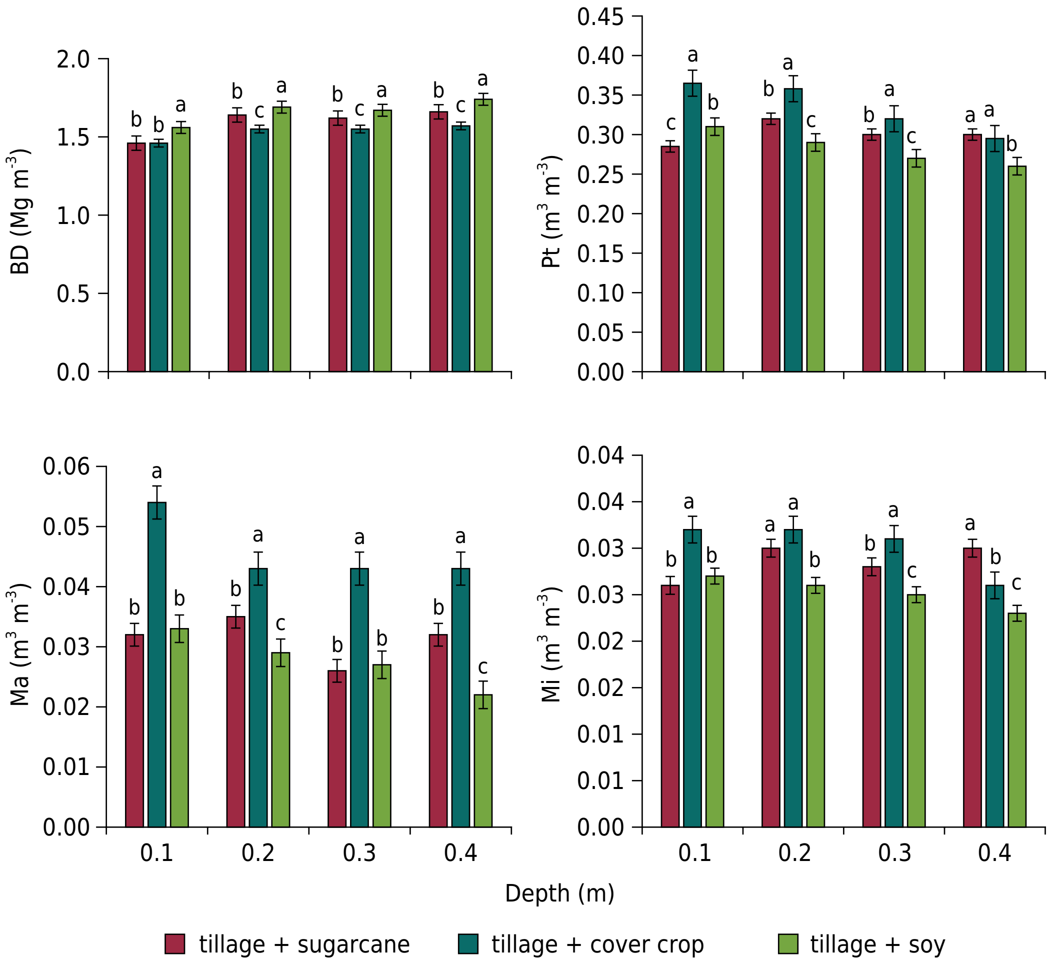

Figure 2. Values of bulk density (BD), total porosity (Pt), macroporosity (Ma), and microporosity (Mi) after 36 months of the renovation period under different management systems: conventional, with green manure or soybean. Equal letters do not differ according to the Scott Knott test ($p<0.05$); ns: not significant. Bars denote the standard error of the mean (n = 8).

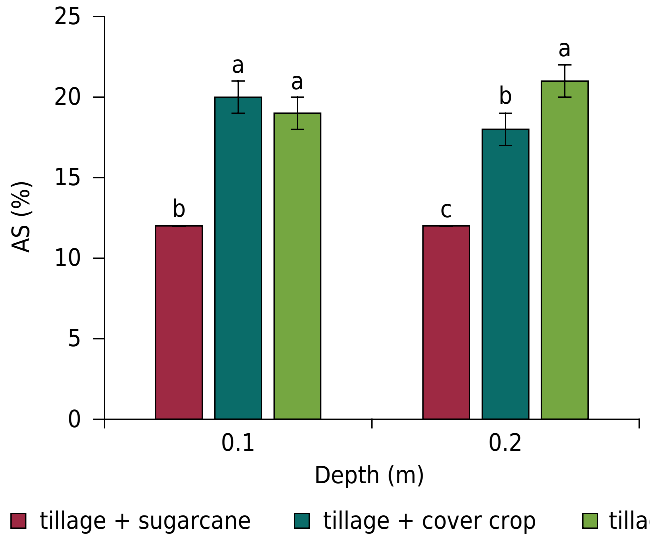

Figure 3. Stability index of soil aggregates, after 36 months of the reform period under different management systems. Equal letters do not differ according to the Scott Knott test ($p<0.05$); ns: not significant. Bars denote the standard error of the mean (n = 8).

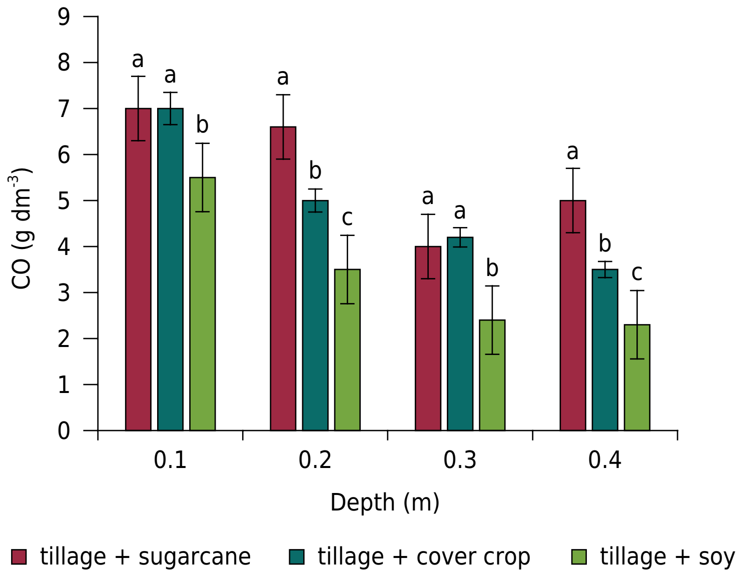

Figure 4. Organic carbon (OC) in the soil after 36 months of the reform period under different management systems. Equal letters do not differ according to the Scott Knott test ($p<0.05$); ns: not significant. Bars denote the standard error of the mean (n = 8).

Table 3. Pearson correlations at the layer of 0.00-0.40 m, between organic carbon (OC) and soil bulk density (BD), total porosity (PT), macroporosity (Ma), microporosity (Mi), and aggregate stability index (ASI)

(OC) "X" (Ds)	r^2 = 0.6239***
(OC) "X" (PT)	r^2 = 0.5215***
(OC) "X" (Ma)	r^2 = 0.4149***
(OC) "X" (Mi)	r^2 = 0.4846***
(OC) "X" (ASI)	r^2 = not significant

Pearson correlations (r^2) tested at 5 and 1 % probability, where: (***) refers to p-value<0.01; and calculated with n = 96.

promoted by the tillage + cover crop system, concerning the tillage + sugarcane and tillage + soy systems, where a greater relationship of these systems with BD was observed (Figure 5b).

DISCUSSION

The advent of mechanization in sugarcane brought challenges related to the different management systems in the period of sugarcane reform in the physical properties of the soil for good development of the crop (Cavalieri et al., 2011). Mechanization is essential for the exploitation of this crop without the need for the use of fire in the harvest. In addition, the perennially of the culture requires that interventions such as turning and subsoiling in the total area be carried out only during the renovation period (Bolonheiz and Gonçalves, 2015) to maintain the physical quality of the soil in sugarcane areas.

Effects of different management systems on physical properties and soil organic carbon

Bulk density and soil porosity

The lower bulk density found in the management system (tillage+cover crop) in the 0.00-0.10 m layer may be related to the greater presence of straw (sugarcane and *crotalaria spectabilis*), which would cause a "dampening effect" by increasing the contact

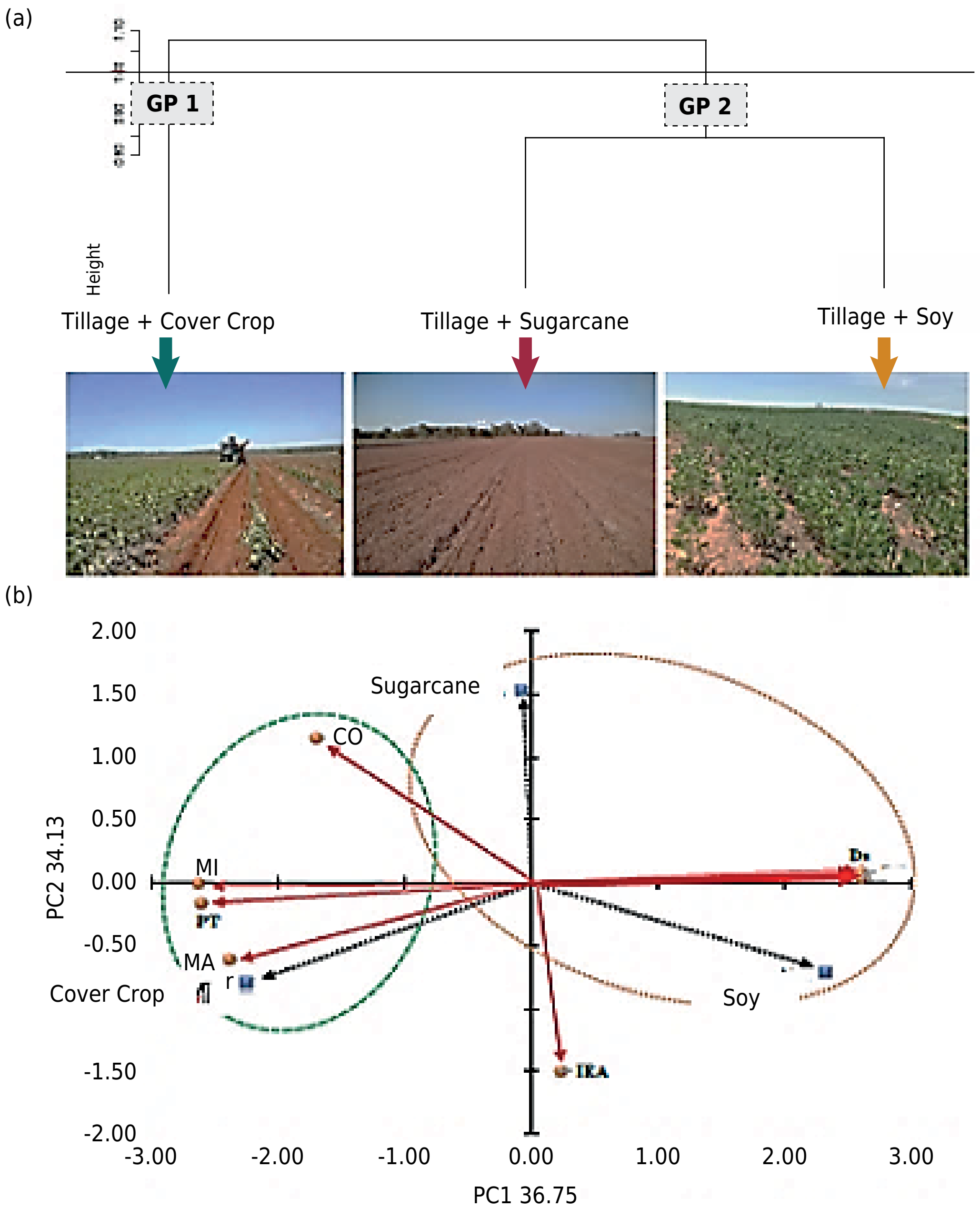

Figure 5. Cluster (a) and principal component analysis (b) demonstrate the relationship between management systems and soil physical attributes after 36 months of the renovation period. Analyses were performed with n = 96, referring to values from all layers.

surface between the wheelset and the ground (Rosim et al., 2012), and thus cause the dissipation of the tension applied to the ground during traffic, reducing compaction (Braida et al., 2006). Below 0.10 m, probably the rooting of *Crotalaria spectabilis*, as well as the incorporation of carbon by the decomposition of the biomass area and senescence of the roots (which also contribute to the formation of bio pores), caused an improvement of the soil structure with positive reflexes in the pore space and density. In addition, the elimination of exudates by the roots, added to the microbiological activity and maintenance of soil moisture by the green manure (Zotarelli et al., 2012), may have enabled the faster formation of macroaggregates, increasing soil cohesion and soil resistance to shear and, thus, reduced soil deformation and porous spaces (Blanco-Canqui and Ruiz, 2018)

Another important detail is the interaction between organic and mineral fractions, which seems to influence the elasticity and friability of the soil due to the formation of bonds between organic and mineral particles and competes to increase the friction and cohesion between the soil particles, making the soil resistance to deformation would be greater (Zhang et al., 1997, 2005; Reichert et al., 2009).

The organic matter added to the soil by the cover crop may have interfered with an increase in the degree of soil elasticity. This is because it is a fraction of high elasticity and its interaction with the mineral fraction causes, after the application of pressure, the return of soil particles to their initial state, thus ensuring the maintenance of porosity (Soane, 1990; Braida et al., 2008). The high water-holding capacity of organic matter can decrease the formation of water films around the mineral particles and, therefore, result in a decrease in the rate of lubrication, reducing the probability of slippage and re-accommodation of soil particles in the soil their empty spaces (Braida et al., 2006).

There is also the fact that the high retention of water by organic matter contributes to the trapping of air bubbles in the soil due to the major difficulty of the expulsion of this in the presence of water (Braida et al., 2008). When the pressure exerted on the soil increases, the air bubbles expand and thus displace the soil, ensuring greater resilience to machine traffic (Hillel, 1998). Still, the greater friability of the soil favors pseudoelastic deformations that are recoverable after the pressure applied to them ceases (Vischi Filho et al., 2015). Therefore, the increase in organic matter influences the limits of soil consistency, which causes less favorable conditions for soil compaction during the pressure exerted by machine traffic.

These results agree with Nicoloso et al. (2008). These authors found that mechanical scarification and the use of cover crops delayed soil reconsolidation when compared to the isolated practice of mechanical scarification. This is probably due to the presence of roots in the initial stage of the soil disaggregated by the conventional tillage, thus delaying the re-accommodation of the particles in the empty spaces, that is, postponing the effects of soil decompaction provided by the conventional tillage operations.

The effects resulting from the tillage+sugarcane management system for the physical properties of the soil, when used in conjunction with organic by-products (application of vinasse in liquid form with high content of K^+ and a low C:N ratio during the renovation period), it is probably linked to the amount of carbon added to the soil and the quality of this organic matter. The application of liquid vinasse would allow a greater percolation of the by-product in the soil profile, increasing its contact with the particles, and this could increase the degree of soil dispersion due to the high concentration of K^+, a monovalent cation that presents high hydration and greater diffuse double layer. In this way, the pores would be sealed, and, therefore, the density and cohesion between the particles would increase (Tavares Filho et al., 2010). In addition, this possible dispersion would also contribute to a greater degree of coating of soil particles by organic residue.

The low C:N ratio of vinasse tends to cause rapid humification of the organic matter present around the mineral particles, increasing the presence of hydrophobic chains in the organic fraction and, in this way, directly collaborating to reduce the rate of soil wetting and reducing its friability (Vogelmann et al., 2013). Therefore, machine traffic tends to occur under conditions of “hard consistency”, allowing the formation of clods, or soil spraying, facilitating the re-accommodation of particles and reducing porous spaces.

Thus, these factors would constitute a recurring cycle with each application of vinasse, that is: increase in the degree of dispersion, coating of particles by organic residues, rearrangement of particles and sealing of porous spaces, increase in density and cohesion between particles, rapid humification of organic matter and increase of hydrophobic chains, reduction of infiltration and wetting rates, reduction of friability and soil mostly traveled under hard consistency. Logically, these hypotheses do not compete to decrease the importance of organic by-products, such as vinasse to incorporate carbon into the soil. However, these results emphasize that perhaps, the tillage+sugarcane combined with the continuous application of vinasse, will accelerate the return of soil compaction.

Higher pore space degradation in the tillage+soy management system compared to the tillage+cover crop management system is probably due to the lower root development of soybean compared to *Crotalaria spectabilis*. This fact would cause faster reconsolidation of the soil with a reduction in its porosity. In addition, the contribution of carbon by soybean biomass is lower than the tillage+cover crop management, which impairs the accumulation of organic matter and reduces the contribution of the organic fraction to the attenuation of physical degradation of the soil. Also, in the tillage+soy handling system, there is greater machine traffic after conventional preparation. Soybean sowing, cultural treatment, and harvesting operations cause additional pressure on the soil and compromise the physical properties of the soil even before the sugarcane crop is planted. Therefore, our results indicate that the use of soybean crops in the period of sugarcane reform in sandy soils may represent a less efficient management system for maintaining the physical properties of the soil throughout the harvest cycles.

Finally, our results indicated that the tillage+cover crop management system reduced compaction (lower BD and greater soil porosity), while the tillage+sugarcane and tillage+soy systems tended to accelerate the return of compaction, probably due to the reorganization of aggregates and compact clods, with a rapid return to the old physical conditions of the soil Barbosa et al. (2018).

Aggregate stability

Aggregates result from the approximation and cementation of mineral and organic soil particles, and their stability indicates the soil’s resistance to erosion and mechanical pressure from the traffic of machines and implements. We know that an aggregate soil with a higher aggregate stability (AS) favors soil aeration, infiltration and retention of water and nutrients, and root development.

Our results showed lower AS values in the tillage+sugarcane management system, probably due to the smaller increments of OC in the soil, which influenced the cementation of the aggregates since, in these sandy soils, the aggregation is mainly due to substances aggregators such as polysaccharides (Rosenzweig et al., 2018). Therefore, the soil under this management will probably tend to have greater susceptibility to the erosive process, given its low capacity for resistance and resilience and the negative effect on crop productivity.

It is known that, in addition to the amount of carbon, the quality of organic matter (C:N ratio) added to the soil also influences soil aggregation. Therefore, the possible addition of vinasse (organic residues with a low C:N ratio) in the tillage+sugarcane management did not favor aggregation, probably due to the high humification rate of the organic fraction and lower reactivity of the organic fraction vis-à-vis soil aggregation. Another point to be considered concerns the addition of K^+ by vinasse. Exchangeble K is a monovalent cation with a high degree of hydration with less force of electrostatic attraction, which favors the dispersion of clay (Zani et al., 2018; Tavares Filho et al., 2010). So, the presence of K^+ in high amounts in the soil solution can increase clay dispersion and cause less stability of the organo-mineral complexes formed (Melo et al., 2020).

The AS values of the tillage+cover crop and tillage+soy managements may be related to the fact that in both, there are no more soil tillage practices after the conventional tillage, that is: in the “PREP+ADV” the plants of cover are used and then the furrows are made for planting the sugarcane, and in the tillage+soy.

Crop rotation with green manures and minimal soil preparation in sugarcane areas provided the largest aggregate diameters (Amaral et al., 2016). The presence of plant residues, coming from cover crops or commercial crops is essential for aggregate stability, and such results tend to be more evident over the years (Calegari et al., 2013).

Organic carbon in the soil

Although the sand fraction predominates in the studied soil (Table 1), which may have influenced the results described previously since the surface area of the clays is much larger (much more reactive) than that of grains of sand. On the other hand, organic matter interacts directly with clays of mineral origin, despite their structural differences, and we have the stabilization of humus molecules (organic matter), which is more difficult in sandy soil without clay crystals.

Therefore, this clay-organic matter interaction probably increases the reactivity of the soil and can promote improvements in physical, chemical, and biological properties, which end up reflecting gains in productivity of exploited crops Murphy (2015). That favors the increase and accumulation of OC (organic carbon) in these soils, which is essential for their agricultural use (Chaplot and Cooper, 2015).

Our results showed that tillage+sugarcane and tillage+cover crop management systems caused greater accumulation of OC in the soil. These results are in agreement with Tenelli et al. (2019), who found a higher OC content with the use of green manure (*Crotalaria spectabilis*) in the renewal of sugarcane fields.

Although the maintenance of straw on the soil surface, resulting from mechanized harvesting, contributes to the addition of carbon (Cerri et al., 2011; Bordonal et al., 2018), there is a predominant effect of the different management systems in the period of reform, in the rate of carbon increment. This is because, when considering the same soil and climate conditions for all areas, this would imply similar straw decomposition factors. In addition, sugarcane straw is characterized by a highly recalcitrant residue, which delays the decomposition and humification process (Galdos et al., 2009). Signor et al. (2014) did not find differences in organic carbon contents in Oxisol, medium texture with 1, 3, and 6 years without burning. This context reinforces that the maintenance of straw may have contributed to the maintenance of the carbon added by managing the different reform systems.

The greater accumulation of carbon in the tillage+sugarcane management system than the tillage+cover crop and tillage+soy systems is probably due to the constant supply of organic by-products (filter cake) after the reform period. The large amount of organic matter deposited in the soil by this by-product can provide a rapid increase in the levels of the organic fraction (Zani et al., 2018). The low C:N ratio of vinasse tends to accelerate the decomposition and humification processes of this organic material in the soil, which thus increases its stability and ensures greater persistence of the organic fraction (Santos et al., 2020); hence, greater amounts of carbon.

In addition, the area with the tillage+sugarcane management has a little more clay (Table 1), and, probably, this higher clay content has directly influenced the physical, chemical, and biochemical protection mechanisms of organic matter. The greater reactivity of the clay fraction in contact with the organic matter may have contributed to this interaction and thus increased the accumulation of carbon in the soil (Dignac et al., 2017).

Regarding the tillage+cover crop management, the high production of biomass on the surface provided by *Crotalaria spectabilis* [from 20 to 30-ton ha^{-1} of green mass (Wutke et al., 2014)], together with the practice of not soil disturbance at the time of planting the crop, possibly made possible the carbon gains. The presence of plant residue on the surface provides moisture maintenance, lower temperature fluctuations, and an increase in microbiological activity in the soil (Menandro et al., 2019), which is an important factor for the decomposition and humification of plant residues (Silva et al., 2014). This carbon increment by the tillage+cover crop management agrees with Ambrosano et al. (2011) and Souza et al. (2019).

Another aspect related to the increase in carbon by the tillage+cover crop management concerns biological nitrogen fixation by *Crotalaria spectabilis*. The nitrogen supply, in this case, may have contributed both to the development of the cover crop and the low C:N ratio, since it is known to limit the availability of nitrogen in sandy soils (Yost and Hartemink, 2019). That would benefit the rapid decomposition of plant residues and the increase of organic matter.

The lower carbon accumulation in the tillage+soy management can probably be explained by the fact that this crop has a low phytomass production (2-to-4-ton ha^{-1}) and a C:N ratio <30 (Wutke et al., 2014). When considering the accelerated decomposition of this phytomass, a condition that favors the stabilization and protection of organic matter in sandy soils (Murphy, 2015), it is observed that the use of soybean crops minimized the increase in carbon levels when compared to other management practices.

Relationships and multivariate analysis between management systems in the period of sugarcane reform, organic carbon, and physical properties of sandy soil

Our results agree with Cherubin et al. (2015; 2016), who showed an association between OC contents and soil porosity (Pt, Ma, Mi). The organic fraction shows high interaction with the mineral fraction thanks to its high specific surface area, its low point of zero charges, and its high concentration of carboxylic, alcohol, and phenolic groups. This increase in OC is the main way to increase the reactivity of the studied soil, rich in quartz and kaolinite, and thus promote improvements in physical, chemical, and biological properties (Dutartre et al., 1993; Murphy, 2015; Donagema et al., 2016; Yost and Hartemink, 2019).

The result of BD is probably related to the fact that the increase in OC contents has influenced: the limits of soil consistency, increasing the water holding capacity and the lubrication rate of the particles, increasing the number of contact points between the particles and the links between the organic and mineral fraction, and increasing the elasticity or decompression coefficient of the soil (Soane, 1990; Zhang et al., 1997, 2005; Braida et al., 2006, 2008; Vasconcelos et al., 2012). All these factors would converge towards the maintenance of porous spaces and less soil compaction.

As for the results of a non-significant correlation between OC and AS, Six et al. (1999, 2002) reported that the aggregation is not restricted only to soil OC, but also to aspects related to soil fauna, wetting and drying cycles, development of the root system and its exudates, texture, and mineralogy. It is possible the occurrence of indirect effects of OC on the EIA, the most important as the retention of moisture with influence on the activity of the edaphic fauna, such as the presence of earthworms that collaborate in the formation of coprolites and in the maintenance of biological cement (Silva Neto et al., 2010).

Regarding the multivariate analysis, the proximity of the management systems tillage+sugarcane and tillage+soy suggests negative influences of these systems in the period of reform in the physical properties of the soil, in comparison to the tillage+cover crop. The tillage+cover crop management system, on the other hand, is an alternative for the sugar-energy sector, vis-à-vis its expansion into areas with sandy soils and degraded pastures (Oliveira et al., 2019) and the problems caused in soil attributes by excessive machine traffic in sugarcane areas (Souza et al., 2019).

CONCLUSION

Tillage+sugarcane and tillage+soy managements negatively affected the physical properties compared to the tillage+cover crop management, whose use of *Crotalaria* *spectabilis* provided higher total porosity, higher macro porosity, and micro porosity, higher aggregate stability. Furthermore, the increase in carbon contents was low, with small variations between treatments.

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