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Conservation systems change soil resistance to compaction caused by mechanised harvesting

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ABSTRACT

Soil compaction in sugarcane plantation has increased in recent times due to intense mechanization of the production process and the increasing axle load of the machines. As such, there are need to evolve conservation systems which will minimize soil disturbance in sugarcane production thereby preventing soil structure degradation and maintain the soil quality, using appropriate compaction models. Thus, the objective of this study was to evaluate the impact of sugarcane harvesting operation under cover crop management systems and soil tillage practices implemented before sugarcane planting using load-bearing capacity models (LBCM). The experiment was set up in a randomised block design with three soil management systems (no tillage, minimum tillage, and minimum tillage combined with a deep subsoiler) and two crop rotations (peanut and sorghum). Soils samples were collected at three depths before and after sugarcane harvesting. The undisturbed soil samples were submitted to the uniaxial compression test, their precompression stress was determined and, afterwards the load-bearing capacity model for each treatment was developed. The load-bearing capacity models showed soil structure degradation under conventional tillage and pasture management, while there was a recuperative effect of soil structure in crop rotation management. However, peanut as a crop rotation made the soil more susceptible to compaction, regardless of soil tillage treatment. At harvest time, the soil was more susceptible to compaction under the following conditions: in the surface layer, with the use of deep subsoiling and with the use of cover crops (peanuts and sorghum). From a practical point of view, this indicates that the better soil physical condition obtained by soil tillage and the use of cover crops can be wiped out by the harvesting operation, thus traffic control actions (including soil moisture and traffic reduction) need to be adopted.

1. Introduction

Comprehension and quantification of soil use and management impacts on physical quality are fundamental to the development of sustainable agricultural systems. The effects of soil tillage on the soil structure depend on the resistance of the topsoil, water content at the time of tillage, agricultural machine traffic intensity, type of equipment, and management of plant residues (Costa et al., 2006). In several situations, conservation systems conducted with minimal soil loosening and crop rotation can maintain soil quality and prevent structural degradation (Severiano et al., 2010).

In Brazil, sugarcane is currently managed under different tillage systems, identified either as conventional tillage, no tillage, and minimum tillage (Bordonal et al., 2018; Farhate et al., 2020). In conventional

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tillage, harrowing is used to remove the residues of the previous cropping, and the soil is turned over, burying the remnant biomass and involving intense disaggregation on soil (0.00–0.40 m), which leads to substantial soil physical functions loss (Bordonal et al., 2017; Barbosa et al., 2019). Minimum tillage system, also referred to as reduced tillage, is a conservationist technique that aims to reduce the number of operations carried out under conventional tillage using lighter equipment, without turning the soil before planting. No-tillage system is a practice widely used in Brazilian farms, nevertheless, it is still not often used in sugarcane cultivation (Cury et al., 2014; Barbosa et al., 2019). This technique is gaining acceptance in sugarcane cropping as a conservationist strategy to preserve soil physical quality (Blanco-Canqui and Ruis, 2018), since soil disturbance is concentrated only in the planting furrow and most part of soil surface remains covered with crop residues.

Soil management systems in sugarcane plantation can exert a substantial influence on sugarcane productivity and longevity since they influence soil compaction. Compaction degree as a consequence of management systems can be determined by evaluating load-bearing capacity (LBC) parameters (Silva and Cabeda, 2006). The LBC defined the ability of the soil structure to withstand tensions induced by machinery traffic without suffering changes in the three-dimensional arrangement of soil particles in a given moisture range or matrix potential (Araujo-Junior et al., 2011). Precompression stress (σ_p) has been adopted as a soil structural quality indicator in LBC studies (Guimarães Júnnyor, b et al., 2019a) since this attribute quantifies the pressure history and represents the maximum pressure to be applied to the soil before additional compaction is observed (Dias Junior et al., 2005; Martins et al., 2018; Tassinari et al., 2019).

Associated with minimum tillage, the use of cover crops presents additional benefits in minimising soil structural degradation. Cover crops have gained prominence as an alternative for crop rotation and, can contribute to soil structure improvements (Lima et al., 2012; Veronese et al., 2012; Otto et al., 2020), to increase C inputs in the soil (Poeplau et al., 2015), enhancing soil aggregation (Reeves, 2018), reducing erosion and providing a favourable environment for the plant growth (Alvarez et al., 2017). In the Brazilian Central-South region, after harvesting (beginning in March and ending in November) and before the new sugarcane planting (new cycle), there is a sufficient period for cover crops to develop. Traditional cover crops include sorghum, millet, peanuts and sunn hemp. Planting cover crops within the sugarcane fallow period could improve soil properties (Farhate et al., 2020; Lovera et al., 2021) and can provide sugarcane yield gains. However, there is little information on the effects of cover crops on soil LBC and susceptibility to compaction (Debiasi et al., 2008).

Soil compaction in sugarcane plantations has been mainly attributed to harvesting operation under inappropriate soil moisture condition (Severiano et al., 2010). Combined with the conventional tillage, that makes the soil more susceptible to compaction, mechanised harvesting is one of the leading causes that limit sugarcane yields and threaten the sustainability of the production system due to soil physical degradation induced by intensive machinery traffic.

This context suggested that cover crop cultivation coupled with conservation tillage practices before sugarcane planting could be a management strategy to minimize soil degradation by mechanical harvesting sugarcane areas, compared to the conventional system. In other words, the adoption of conservation tillage with cover crops before sugarcane cultivation could enhance soil's physical quality and affects soil LBC, so that the soil becomes more resistant to the pressures made by the machines traffic.

Thus, understanding how soil management in sugarcane affects soil LBC, considering soil disaggregation and the use of cover crops, can become the basis for the development of a management strategies aimed at achieving sustainability in sugarcane production, leading to increased sugarcane plantation productivity and cycle longevity.

This study had the objective of evaluating the impact of mechanized sugarcane harvesting on soil compaction, considering diverse cover crops and soil tillage practices, through precompression stress (σ_p) and load-bearing capacity models (LBCM).

2. Materials and methods

2.1. Study site location

The experiment was carried out in Ibitinga (São Paulo State, Brazil) (21° 45' S, 48° 49' W, 455 m a.s.l.). The climate of the region is classified as a tropical humid climate, with dry winters and rainy summers according to the Köppen classification (Alvares et al., 2013), with an average annual temperature of 22.9 °C and an average precipitation of 1260 mm (CEPAGRI, 2019).

The soil of the experimental area is classified as Haplic Acrisol according to the Food and Agriculture Organization of the United Nations - FAO system (IUSS Working Group WRB, 2015), with a sandy loam texture at the A horizon and sandy clay at the B horizon (Table 1).

2.2. Field treatments

The experimental area was cultivated with a long-term pasture (more than 12 years) in an extensive system. In December 2014, the field was tilled with a disk harrow (with 36-N^{os} 32-inch disks) which was pulled with a Valtra BH 180 tractor. Harrowing was followed by subsoiling with a seven-shank subsoiler, with a working depth of 0.40 m drawn by a Case IH model MX tractor.

The experiment was set up as a randomised block design (RBD) in a subdivided plot scheme comprising eight treatments (Table 2), with three repetitions for each treatment. Each plot consisted of six sugarcane lines of the CTC4 variety with a spacing of 1.5 m and 30 m in length, encompassing an area of 300 m^2 per plot.

The chronological order of the events in the study area is shown in Fig. 1.

The cover crops were planted soon after primary tillage in the area and cultivated for four months. The mechanised sowing of peanut (*Arachis hypogaea* L.) and sorghum (*Sorghum bicolor* L.) was performed with a Baldan model 4000 SPA Megaflex precision seeder at rates of 110 and 10 kg seeds ha^{-1}, respectively. The seeder was pulled by a Valtra model BM 125i tractor. The peanut was mechanically harvested with a Sweere Double Master V peanut harvester pulled by a Massey Fergusson model 7140 tractor. Sorghum was mechanically cut with a mower connected with a Massey Fergusson model 7140 tractor (the same tractor used in the peanut harvester).

Soil tillage after the cultivation of cover crops (peanut and sorghum) and before planting sugarcane depended on the sugarcane cultivation system investigated (Table 3). The conventional tillage treatment was performed using two light harrowings with a Baldan hydraulic harrow with 36 disks of 32-inch. For the minimum tillage systems, subsoiling was performed with a Stara Asa Laser subsoiler with five shanks. The implement was drawn by a Case IH model Magnum 270 4 × 2 tractor.

Water content during sugarcane harvest was 0.09, 0.09 and 0.14 kg kg^{-1} at the 0.10–0.13, 0.25–0.28, and 0.40–0.43 m layer, respectively. Detailed information about the machines used in sugarcane planting and harvesting operations can be found on our previous paper (Guimarães Júnnyor et al., 2019b).

2.3. Soil sampling

Soil samples with an undisturbed structure were collected from the agricultural traffic line before sugarcane harvesting, at three sampling points per experimental plot, along a diagonal line. For each treatment, 12 undisturbed samples were collected at 0.10–0.13, 0.25–0.28, and 0.40–0.43 m depths, totalling 288 samples (4 samples × 3 sampling points × 3 depths × 8 managements), with an Uhland sampler and stainless-steel cylinders (diameter 0.07 m, height 0.025 m). These samples were used to generate the soil load-bearing capacity models

Table 1
Physical characterization and texture descriptions of the Haplic Acrisol of the experimental area in Ibitinga, SP, Brazil.

Horizon	Depth	Mac[1]	Mic[1]	TP[1]	Bd[2]	Pd[2]	Sandy[2]	Silt[2]	Clay[2]	Texture[3]
	(m)	$m^3\ m^{-3}$			$kg\ dm^{-3}$		$g\ kg^{-1}$			
Ap1	0.10–0.13	0.20	0.24	0.44	1.58	2.65	780	60	160	Sandy loam
AB	0.25–0.28	0.13	0.25	0.39	1.73	2.73	650	60	290	Sandy clay loam
Bt1	0.40–0.43	0.14	0.30	0.44	1.58	2.79	510	40	450	Sandy clay

[1]The macroporosity (Mac), microporosity (Mic) and total porosity (TP) were determined according to the standard Teixeira methodologies (Teixeira et al., 2017). [2]Particle size distributions, bulk density (Bd) and particle density (Pd) were determined according to Blake and Hartge (1986a, b). [3]Soil taxonomy descriptions were derived from the particle size distributions according to the texture classification scheme of the Department of Agriculture of the USA (USDA, 2017). n = 12 per depth.

Table 2
Identification of the eight treatments that combined cover crops and soil management.

Crop rotation	Soil management	Label	Specifications
None	Pasture	PA	Prior to the installation of the experiment
None	Conventional tillage	CT	Soil tillage with two light harrowing
Sorghum	Minimum tillage with deep subsoiler	DTS	Soil loosened to a depth of 0.70 m
Peanut		DTP	
Sorghum	Minimum tillage with subsoiler	MTS	Soil loosened to a depth of 0.40 m
Peanut		MTP	
Sorghum	No-tillage	NTS	No tillage for sugarcane planting
Peanut		NTP	

*The pasture area was used as reference for the attributes, since it represents pre-experimental physical soil attributes.

(LBCM), which represent the initial state of soil strength from which we evaluated whether there was or not any significant additional compaction after the harvesting operation.

Immediately afterward the sugarcane harvesting, added 144 soil samples [2 samples x 3 sampling points x 3 depths x 8 managements] were collected. These samples were used to evaluate the impact on soil strength from the mechanised sugarcane harvesting operation based on LBCM.

The samples were covered in plastic film and then in paraffin wax to preserve their original field moisture as well as their structure during transportation.

2.4. Soil analyses

2.4.1. Particle size distribution and particle density

The particle size distribution and particle density (Pd) were determined according to Blake and Hartge (1986a).

2.4.2. Uniaxial compression test

Undisturbed samples collected before sugarcane harvesting were prepared and saturated for 48 h by capillarity. They were equilibrated to the following matric potentials (Ψm): −0.002, −0.01 using tension tables (Dane and Hopmans, 2002); and −0.10 and −1.5 MPa using Richard's membrane-plate extractor (Klute, 1986).

After the hydraulic equilibrium, each sample was weighed and subjected to the uniaxial compression test according to Bowles (2001), at the following loads: 25, 50, 100, 200, 400, 800, and 1600 kPa. Normal stress was applied sequentially, i.e., each tension was applied until 90% of the maximum deformation was reached (Taylor, 1948), followed by the next load. The test was performed using a pneumatic

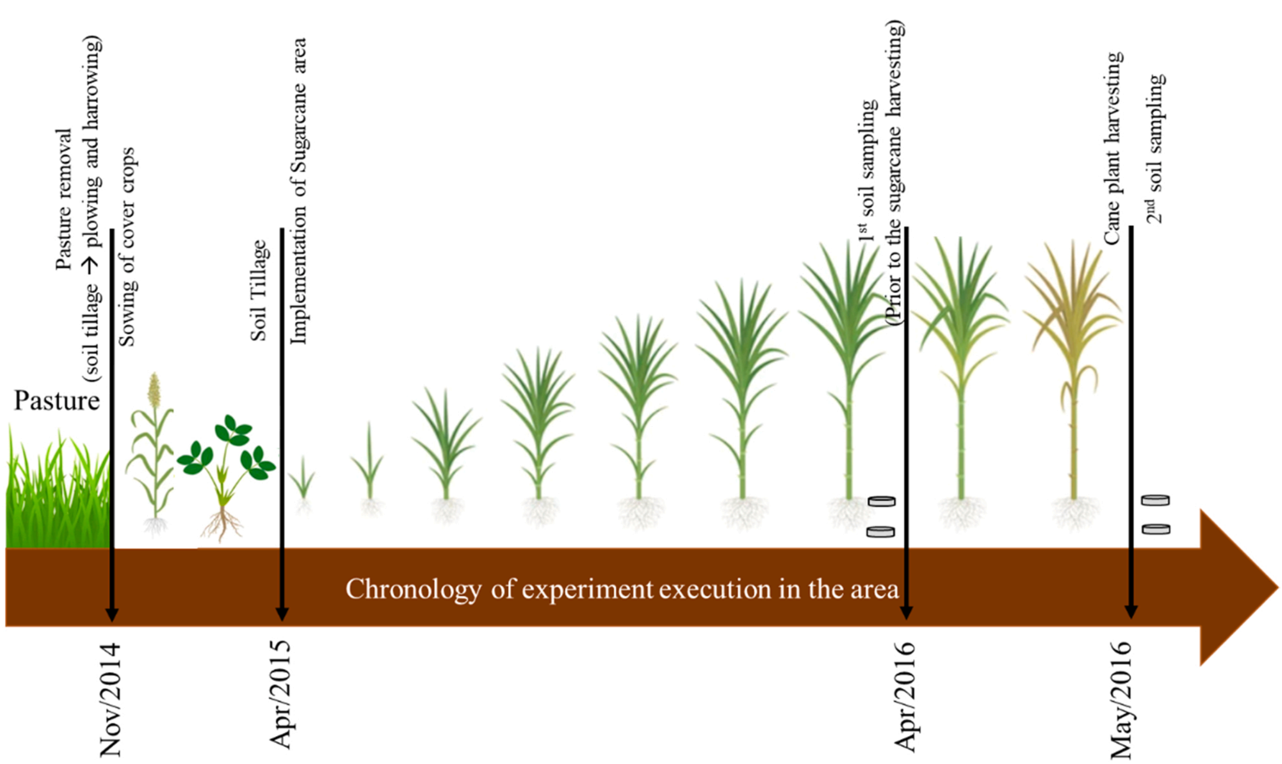

Fig. 1. Timeline of field experiment steps from initial soil tillage before cover crops to sugarcane harvesting operation.

Table 3
Classification of preconsolidation pressure values determined after the sugarcane harvesting operations in traffic lane for Haplic Acrisol under different uses and soil management systems, at three depths in Ibitinga (state of São Paulo), Brazil.

Uses and soil management systems	Depth (m)		
	0.10–0.13 *	0.25–0.28 *	0.40–0.43 *
% of soil samples with σ_p in the region a - with soil compaction			
Conventional tillage - CT	33	67	0
Sorghum with no-tillage - NTS	83	100	0
Sorghum with minimum tillage - MTS	67	100	0
Sorghum with a minimum tillage with deep subsoiler - DTS	0	83	100
Peanut with no-tillage - NTP	100	67	100
Peanut with minimum tillage - MTP	100	83	100
Peanut with a minimum tillage with deep subsoiler - DTP	100	100	100
% of soil samples with σ_p in the region b - did not suffer soil compaction. but with a tendency to compact			
Conventional tillage - CT	67	33	50
Sorghum with no-tillage - NTS	17	0	100
Sorghum with minimum tillage - MTS	33	0	100
Sorghum with a minimum tillage with deep subsoiler - DTS	33	17	0
Peanut with no-tillage - NTP	0	33	0
Peanut with minimum tillage - MTP	0	17	0
Peanut with a minimum tillage with deep subsoiler - DTP	0	0	0
% of soil samples with σ_p in the region c - without soil compaction			
Conventional tillage - CT	0	0	50
Sorghum with no-tillage - NTS	0	0	0
Sorghum with minimum tillage - MTS	0	0	0
Sorghum with a minimum tillage with deep subsoiler - DTS	67	0	0
Peanut with no-tillage - NTP	0	0	0
Peanut with minimum tillage - MTP	0	0	0
Peanut with a minimum tillage with deep subsoiler - DTP	0	0	0

*Total number of samples obtained after harvesting operations was six in each plot and each depth.

consolidometer developed by Figueiredo et al. (2011). Then, the samples were dried in an oven for 48 h at approximately 105 °C to determine bulk density (Bd) and volumetric water content (θ) (Blake and Hartge, 1986b).

2.4.3. Precompression stress measurements and statistical analyses

A soil compression curve of each sample was obtained by plotting the logarithm (base 10) of the applied pressure on the *x-axis* versus the soil deformation on the *y-axis*. Precompression stress (σ_p) was determined according to the method described by Dias Junior and Pierce (1995). These values were adjusted as a function of the soil water content (θ) to obtain the soil load-bearing capacity models (LBCM; modified Araujo-Junior et al., 2011):

$$\sigma_p = 10^{(a+b\theta)} \tag{1}$$

which can also be written as:

$$\log \sigma_p = a + b\theta \tag{2}$$

This equation defines the load-bearing capacity model, where σ_p is precompression stress, θ is the volumetric water content, and “a” and “b” represent the empirical parameters obtained from fitting the model.

The regressions were adjusted using SigmaPlot software, version 12.0 (Jandel Scientific), to obtain the load-bearing capacity model, according to the equation proposed by Dias Junior and Pierce (1995) and modified by Araujo-Junior et al. (2011). These models were obtained prior to the sugarcane harvesting operations and represent the initial strength level of the soil. The estimated soil equations were compared according to the procedure described by Snedecor and Cochran (1989), which includes a homogeneity test for data (F-test), the angular coefficient (b), and the significance of the linear coefficient (a) from the linearised equation (Eq. 2) at the evaluated depths within each management system.

Samples collected after the harvesting operations were submitted to the uniaxial compression test at field moisture. Their precompression stress (σ_p) and water content (θ) values were plotted on soil load-bearing capacity models (LBCM) obtained prior to traffic in the sugarcane harvesting for each management system. The procedure from Dias Junior et al. (2005), Guimarães Júnnyor et al. (2019a), and Tassinari et al. (2019) was adopted. This analysis checks whether there was an increase in soil strength or not by plotting the precompression stress and water content values from the samples collected after traffic in the LBCM graphs (Fig. 2).

The σ_p values, obtained in accordance with Dias Junior and Pierce (1995), were plotted in the previously obtained LBCM, including limits of the 95% confidence interval (Fig. 2) and classified as compacted (values above upper limit), with a tendency to compact or steady condition, and not compacted (values below lower limit). The LBCM represents the initial condition (prior to the sugarcane harvesting mechanized operations) and the samples located region defined values below the lower limit of the 95% confidence interval (region “c” in Fig. 2) are considered not compacted, and the samples located between the limits of the 95% confidence interval of the population (region “b” in Fig. 2) indicates a steady condition. The samples that fall within this region are considered not to have yet endured additional compaction. The samples located above the upper limit of the 95% confidence interval (region “a” in Fig. 2) are considered compacted.

The number of samples in each region (“a”, “b” and “c”) were organized into a contingency table, with the soil management systems in the columns (variables) and the soil depths in the rows (individuals).

3. Results and discussion

3.1. Comparison of the load-bearing capacity models

The load-bearing capacity models (LBCM) for management systems in each depth (Fig. 3) and its coefficients of determination and the level of significance (Appendix A) showed different strength attributes in the soils among management systems. The linear parameter “a” of the soil load-bearing capacity models ranged from 2.68 for the deep tillage subsoiler in sorghum cultivation to 3.50 for no tillage in sorghum cultivation, and the angular parameter “b” ranged from 1.28 for pasture

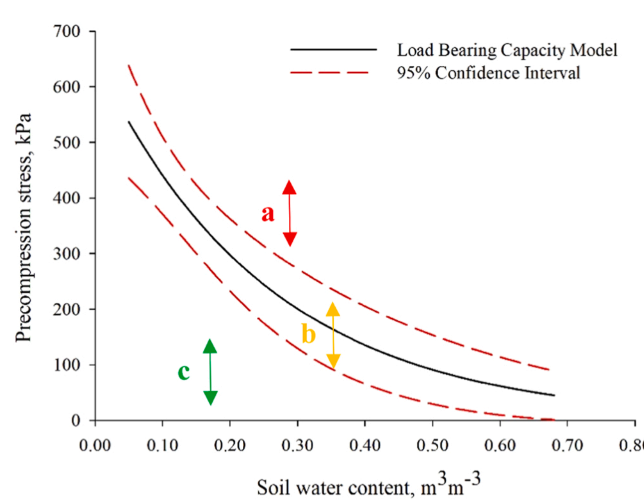

Fig. 2. Criteria to assess additional compaction after sugarcane harvesting. The regions ‘a’ indicates additional soil compaction, region ‘b’ represents a steady condition and, region ‘c’ indicates no additional compaction.
Adapted from Dias Junior et al. (2005), Guimarães Júnnyor et al. (2019a) and Tassinari et al. (2019).

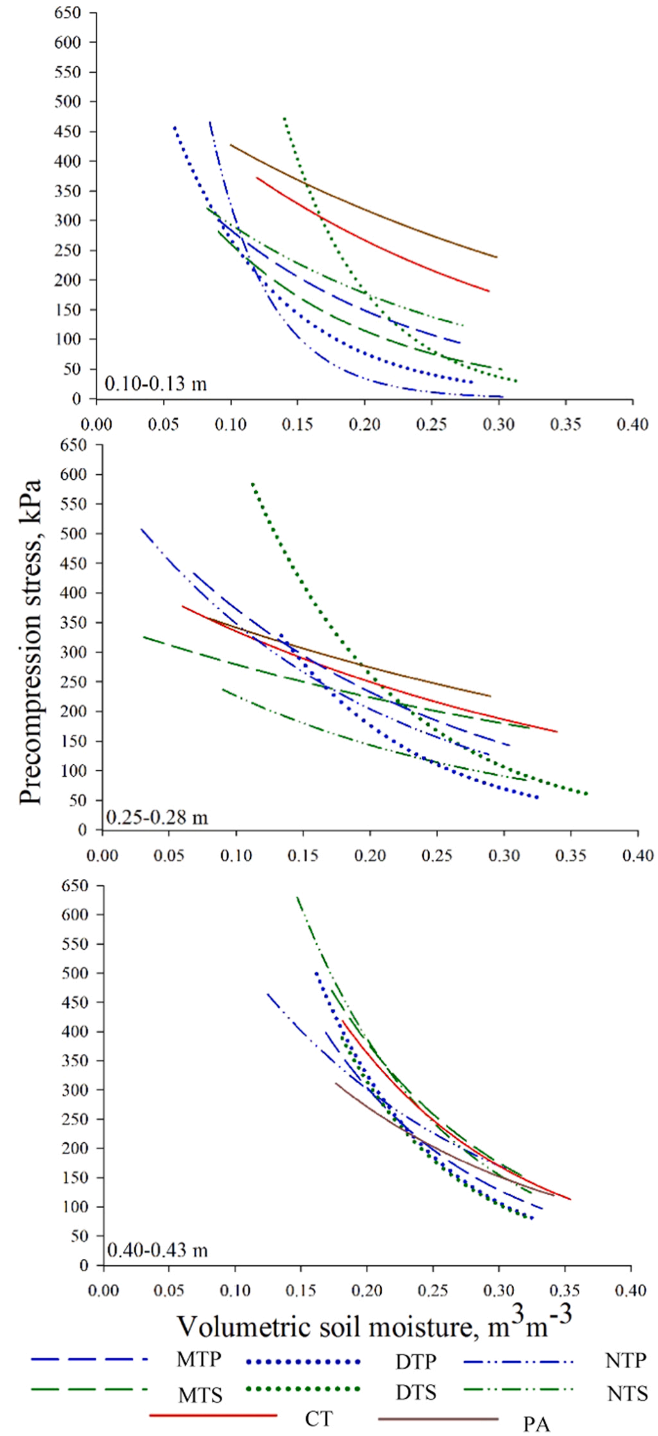

Fig. 3. Load bearing capacity models in traffic lane for Haplic Acrisol under different uses and soil management systems, at three layers (0.10–0.13 m, 0.25–0.28 m and 0.40–0.43 m) in Ibitinga (São Paulo State), Brazil. PA: Pasture: CT: conventional tillage; MTP: peanut with minimum tillage; DTP: peanut with a minimum tillage with deep subsoiling; NTP: peanut with no-till; NTS: sorghum with minimum tillage; DTS: sorghum with a minimum tillage with deep subsoiling; NTS: sorghum with no-till;.

to 9.91 for no tillage in peanut cultivation at a soil layer of 0.10–0.13 m depth.

The method described by Snedecor and Cochran (1989) to compare the preconsolidation pressure models (Appendix B) was followed to group mutually homogeneous linear regression equations and the non-significant coefficients of the regressions and, to fit new models considering all values of σ_p and θ (Figs. 4–6).

In the 0.10–0.13 m layer, CT and PA treatments presented a higher LBC in relation to the other management systems for the entire moisture range (Fig. 4).

Greater resistance to compaction in pastures is generally limited to topsoil and, related to the presence of pasture roots, which promoted more stable aggregates due to the contribution of organic residues, root exudates, and to the mechanical action of the roots, which provided increases in precompression stress (Debiasi et al., 2008). The greater resistance in PA treatment is also consequence of soil consolidation through the pressure exerted by grazing animals and the absence of tillage in soil management.

In CT, effects on the Bd were likely eliminated by subsequent traffic. The higher σ_p values evidencing the greater soil resistance to compaction for these treatments, as a function compaction state in CT, due to soil rearrangement of the soil particles by agricultural machinery traffic soon after initial preparation, evidenced the soil structure degradation (Guimarães Júnnyor et al., 2019a). Conventional tillage decreases soil compaction briefly, as the traffic immediately afterwards on the loosening soil promotes increases Bd and consequently increases the load-bearing capacity.

In the same layer, minimum tillage with a deep subsoiler for peanut (DTP) and sorghum (DTS) and NTP and MTS managements, which presented similar LBC according to the test procedures by Snedecor and Cochran (1989) (Appendix B), provided a lower LBC to Acrisol soil. This lower LBC can be attributed to the sorghum and peanut crop residues and to the soil tillage in these management strategies, which promote the reduction of initial bulk density and can be reflected in a greater susceptibility to additional compaction. In general, the increasing order of soil structure change was DTS = DTP = MTS = NTP < MTP < NTS < CT = PA (Fig. 4).

The lowest soil LBCM in the 0.10–0.13 m layer was observed for peanut with minimum tillage at a moisture up to 0.15 m^3 m^{-3} (Fig. 4), while at a higher moisture content (> 0.16 m^3 m^{-3}), the LBCM presented lower resistance to compaction using minimum tillage with a deep subsoiler for peanut and sorghum and NTP and MTS systems. Crop rotations act in structuring, forming, and stabilizing aggregates in the soil (Wohlenberg et al., 2004) due to the addition of organic residues, root exudates, and to the mechanical action of the roots. The adoption of crop rotations provides a better soil structure than conventional tillage, that is traditionally utilized in the sugarcane production in Brazil, which promotes intense disaggregation on soil, substantial losses of soil carbon and physical functions leading to degradation of soil structure (Bordonal et al., 2017; Silva-Olaya et al., 2013).

Comparing the PC + PA LBCM model with crop rotation LBCM models, either with peanut or sorghum, using soil tillage with a disk

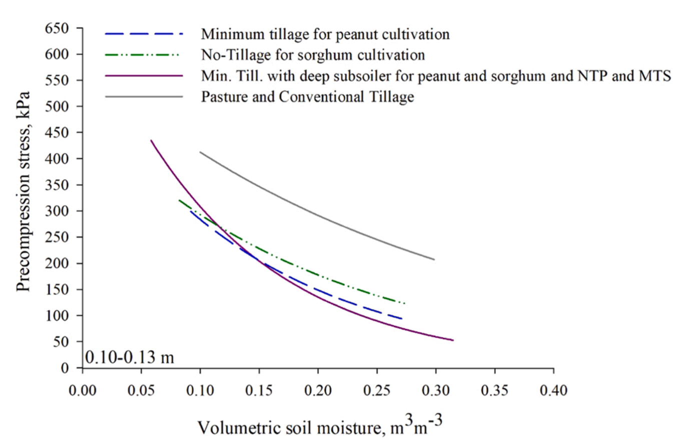

Fig. 4. Load bearing capacity models in traffic lane for Haplic Acrisol under different uses and soil management systems, in the 0.10–0.13 m layer. MTS: minimum tillage for sorghum; NTS: no-tillage for sorghum.

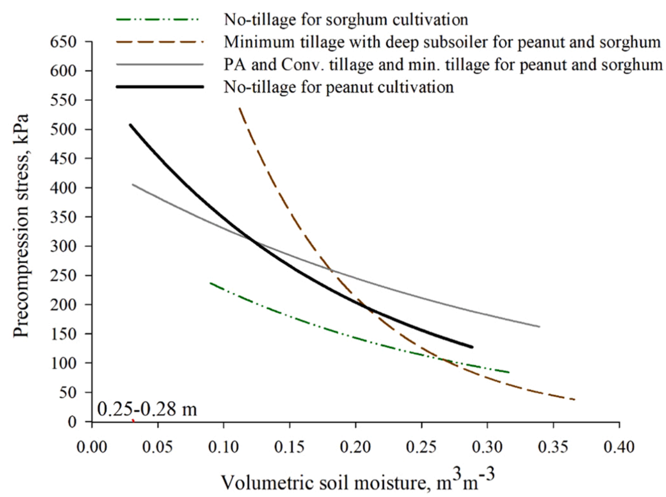

Fig. 5. Load bearing capacity models in traffic lane for Haplic Acrisol under different uses and soil management systems, in the 0.25–0.28 m layer.

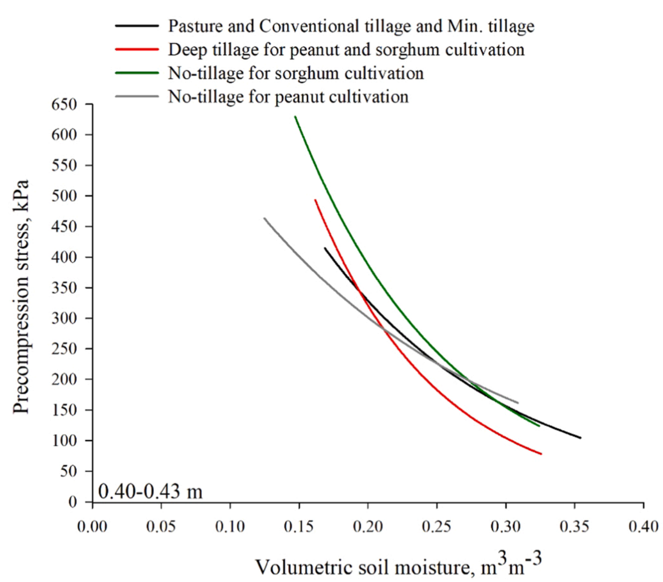

Fig. 6. Load bearing capacity models in traffic lane for Haplic Acrisol under different uses and soil management systems, in the 0.40–0.43 m layer.

harrow and without crop rotation, the soil was unprotected and thus direct contact with equipment wheels occurred during traffic, which promoted an increase in LBC in the 0.10–0.13 m layer. The LBCM of the crop rotation management system was more susceptible to compaction than the CT + PA LBCM (Fig. 4). This higher susceptibility can be associated with a positive effect of crop rotation in the soil structure, observed by a reduction in Bd and an increase in porosity, evidencing the recuperative effect of the soil structure using crop rotation.

In the 0.25–0.28 m layer the LBCMs were similar for the CT = PA = MTS = MTP = NTP systems, as well as for the DTS = DTP treatments (Appendix B). Therefore, all σ_p and θ data were pulled together to construct a three new LBCMs in this soil layer: CT + PA + MTS + MTP, NTP, NTS, and minimum tillage with a deep subsoiler for sorghum and peanut cultivation (DTS + DTP). The following discussion considered the new LBCM (Fig. 5).

The sorghum no-tillage management system (NTS) presented lower LBC for the 0.25–0.28 m layer until a moisture value of 0.28 m^3 m^{-3} (Fig. 5). For higher moisture levels, the lower LBC was observed using minimum tillage management with a deep subsoiler, demonstrating that the soil tillage system was more susceptible to soil compaction at a higher soil moisture content. The lower LBC for DTS and DTP in higher moisture conditions was related to lower Bd and higher macroporosity, i.e., the soil was less resistant to compaction with increasing moisture. In contrast, the management system minimum tillage with a deep subsoiler (DTS + DTP) presented more resistance to soil compaction in lower moisture conditions (< 0.19 m^3 m^{-3}). The observed result for DTS + DTP is, thus, likely due to greater soil aggregate stability.

For moisture values higher than 0.19 m^3 m^{-3}, the CT + PA + MTS + MTP management system presented a higher LBC, indicating that this management system was the most resistant to soil compaction in higher moisture conditions. This behaviour may be associated with higher Bd values and, consequently, a lower macroporosity for Acrisol soil in the 0.25–0.28 m layer.

LBCMs were the same in the 0.40–0.43 m layer for CT + PA + minimum tillage for sorghum and peanut (MTS + MTP), minimum tillage with deep tillage for peanut and sorghum (DTS + DTS), and NTP and NTS soil management (Appendix B). Thus, a new equation was fitted to each data set, considering all σ_p and θ values (Fig. 6).

No tillage in the peanut soil management system (Fig. 6) led to a lower LBC up to a soil moisture of 0.21 m^3 m^{-3} for the 0.40–0.43 m layer, while for a higher soil volumetric moisture level, the minimum tillage with deep tillage for peanut and sorghum (DTP + DTS) management system resulted in a lower LBC compared to the other soil management systems. At a lower soil moisture content, no tillage for the sorghum cultivation (NTS) management system demonstrated greater resistance to compaction in relation to other management systems. However, with increasing soil water content, a greater distance between the LBCM's, indicating that the saturation degree had an effect on precompression stress and that increase moisture resulted in the decrease of LBC.

3.2. Evaluation of sugarcane harvesting operation

The proportion of compacted soil samples after harvesting operations compared to soil conditions prior the traffic in each of management system studied ranged from 0% to 100% (Table 3), varying with the depth. For the 0.10–0.13 m layer, only soil samples from DTS (sorghum+deep subsoil) stayed in the region with no additional soil compaction (67% in the region "c"). Samples of all other systems had additional compaction or tendency to compaction. Peanut as a cover crop resulted in 100% of samples with additional compaction, for all tillage systems (NTP, MTP and DTP). For sorghum, most of NTS samples (83%) and MTS samples (67%) presented additional compaction, while the remaining 17% and 33% respectively presented a tendency for compaction. Conventional tillage presents the lowest percentage of samples with soil compaction (33% in region "a"), but all other samples has a tendency to compact (67% in region "b") and, none were classified as without soil compaction.

Additional compaction due to sugarcane harvesting that already occurred in 100% of samples of the management systems with peanut as cover crop is due to soil turning and rearrangement throughout peanut harvesting. In peanut harvesting plant removal is carried out by equipment through the penetration of cutting blades to a depth of approximately 0.05 m below the plant pods. This results in a disaggregated soil surface, similar to what occur in soil tillage operations (Oliveira et al., 2003), which support lower loads compared to areas where sorghum was cultivated. This additional compaction in peanuts areas could be associated to low straw production and low percentage of mulching cover area. Peanuts as cover crop can provide additional benefits as increase in soil fertility, decrease in the incidence of insect and pathogens, weeds control but represent a risk to soil compaction.

In contrast, the precompression stress values measured after sugarcane harvesting in CT in the 0.10–0.13 m layer indicated that harvesting operation impacts were low in this system (33% of samples with additional compaction). This denoted compaction in the initial conditions of soil in CT, as indicated in the LBCM (Fig. 4), that reflected the tension history and accumulation of the implement loads, starting with the plough pan and disk harrow for soil tillage and other machineries used in sugarcane cultivation that exerted pressure on the soil. Soil compaction in CT management in sugarcane cultivation, evaluated by increases in Bd and microporosity, as well as decreases in macroporosity, was also reported in Paulino et al. (2004).

In the 0.25–0.28 m layer, there were no samples with no compaction (region "a") after sugarcane harvesting (Table 3). Most of the σ_p values for all managements were observed in region "a", with 100% of samples in NTS, MTS and, DTP, 83% in DTS and MTP, 67% in CT and MTP managements showing additional compaction after harvesting. Even for the systems with greater soil load-bearing capacity (Fig. 5) and consequently lower susceptibility to compaction, the mechanized operations carried out in the harvesting of sugarcane induced additional compaction. In areas cultivated with sugarcane, degradation of the soil structure up to the 0.30 m layer in the traffic lane had been reported (Souza et al., 2015). Similar results were obtained by Severiano et al. (2010) and Esteban et al. (2019) in Oxisol soil and in two types of soils (Oxisol and Cambisol), which showed the presence of a compacted soil layer above 0.30 m after harvesting in areas cultivated with sugarcane under conventional tillage system.

The 0.40–0.43 m layer (Bt horizon) was more resistant to compaction (Fig. 6) due to its lower sand content in the Bt horizon (Table 1). Soil susceptibility to compaction increased with increasing soil sand content (Martins et al., 2018) because of the higher packing capacity as a function of the irregular shape of the sand particles. In spite of that, in 0.40–0.43 m layer 100% of the samples presented additional compaction after harvesting in the DTS, DTP, NTP, and MTP management systems (Table 3). Also, in the NTS and MTS management systems 100% of the samples presented a trend for compaction (region "b"). Only in CT management system there was samples that did not present additional soil compaction, with 50% of the samples in region "c" and, the remaining 50% presenting a trend for compaction. Other authors observed compacted layer between 0.30 and 0.45 m in conventional tillage areas after sugarcane harvesting, as Marasca et al. (2015) in an Oxisol, Pacheco and Cantalice (2011) in the Bt horizon of an Acrisol and, Tassinari et al. (2019), who noted a tendency for higher compaction in the Bt horizon than in the superficial soil layer.

Conventional tillage under the present study presented soil compaction prior to sugarcane harvest resulting in greater mechanical resistance of the soil as tillage effects were eliminated by subsequent traffic. That can be beneficial for agricultural trafficability, although it may, in contrast, limit roots sugarcane growth and development.

On the other hand, the no-tillage (NT) system, with no soil disaggregation by tillage implements, was expected to present greater resistance to external stress in relation to the other systems. However, even with sorghum as cover crop, NT presented most of the samples with additional compaction after harvesting at 0.10–0.13 and 0.25–0.28 m layers.

Harvesting operations in the sugarcane, according to the LBCM (Table 3), led to different compaction susceptibility between layers, being 0.10–0.13 m < 0.25–0.28 m < 0.40–0.43 m. However, there are some additional practical implications. Although the surface horizon presents less resistance to compaction because of its coarse texture, it retains less moisture over time. Unlike the clayey subsoil horizon layer, more resistant to deformation, that may remain wetter and thus more prone to compaction. According to Santos et al. (2014), this is very important in soils that typically have a denser and naturally Bt horizon compact layer.

4. Conclusions

Disruption of soil structure on soil surface by soil tillage implements produces a condition that makes the soil more susceptible to compaction. At harvest time the soil was more susceptible to compaction under the following conditions: in the surface layer, with the use of deep subsoiling and cover crops (peanuts and sorghum). From a practical point of view, this indicates that the better soil physical condition obtained by soil tillage and the use of cover crops can be wiped out by the compaction caused on harvesting operation. Traffic control actions need to be adopted.

CRediT authorship contribution statement

Wellingthon da Silva Guimarães Júnnyor: Conceptualization, Methodology, Validation, Investigation, Data curation, Writing – original draft, Visualization, Writing – review & editing, Funding acquisition. **Isabella Clerici De Maria:** Conceptualization, Methodology, Validation, Investigation, Data curation, Writing – original draft, Writing – review & editing, Funding acquisition. **Cezar Francisco Araujo Junior:** Formal analysis, Investigation, Data Curation, Writing – original draft. **Etienne Diserens:** Formal analysis, Investigation, Writing – original draft. **Eduardo da Costa Severiano:** Formal analysis, Investigation, Writing – original draft. **Camila Viana Vieira Farhate:** Conceptualization, Investigation, Data curation, Writing – original draft. **Zigomar Menezes de Souza:** Formal analysis, Writing – original draft Funding acquisition.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Wellingthon da Silva Guimaraes Junnyor reports financial support was provided by FAPESP.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.indcrop.2022.114532.

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