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RESEARCH ARTICLE

Soil Load-Bearing Capacity and Development of Root System in Area Under Sugarcane with Traffic Control in Brazil

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Abstract Attempts to achieve reduced traffic area and favorable conditions for sugarcane field durability have been made increasingly necessary to use traffic control techniques in areas of sugarcane production. Our goal was to assess the benefits of traffic control for sugarcane cultivation areas by using a load-bearing capacity modeling and developing a root system. Our experiment was conducted in a sugarcane cultivation area in the region of Nova Europa, São Paulo, Brazil, by assessing the following treatments: *T*1 = sugarcane planted with row spacing of 1.50 m managed without autopilot; *T*2 = sugarcane planted with row spacing of 1.50 m managed with autopilot; *T*3 = sugarcane planted with row spacing of 1.5 $\times$ 0.90 m managed with autopilot. Soil sampling occurred at layers of 0.00–0.15 and 0.15–0.30 m in inter-row center and seedbed region. Our results reveal that the use of autopilot in the seedbed area is less influenced by machinery traffic, which guarantees preserved soil structure maintenance in the plant row region. Mathematical models of the inter-row center presented higher load-bearing capacity values than the seedbed region for all treatments, layers, and cycles assessed. Additionally, load-bearing capacity increases as the sugarcane cultivation cycles evolve, including higher soil load-bearing capacity at the first ratoon cane cycle in relation to the cane-plant cycle. Finally, the sugarcane crop root system has good distribution during the cane-plant cycle; however, the first ratoon cane cycle has a downward trend for the plant rows in the inter-row center because of intensive machine traffic.

Keywords Entisols Quartzipsamments · Soil compaction · Soil structure · Modeling · Soil physics · Root growth

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Introduction

Soil compaction process has been suggested to result from the replacement of manual harvesting with mechanized sugarcane crop harvesting, which also causes reduced porous space and possibly leads to low productivity values for sugarcane plantations (Cheong et al. 2009; Roque et al. 2011).

Soil compaction causes an increase in soil penetration resistance, which is directly related to some biological variables, such as lower growth of plants root system, compromising the efficiency of water and nutrient absorption (Gao et al. 2012; Sousa et al. 2013). Therefore, it has been increasingly recommended to manage sugarcane crops with controlled traffic as an alternative to mitigate issues related to soil compaction (Cheong et al. 2009).

The use of autopilot technique has proven promising considering its basic principle to predetermine the path of a machine by using a system which projects a set of guidelines with defined spacings and establishes the places where traffic should occur (Oliveira and Molin 2011). In addition, over the past few years, this technology has become largely applied both in the Brazilian agricultural scenario and worldwide; in 2013, for example, the USA started using autopilot in 82% of their agricultural areas (Holland et al. 2013).

Another autopilot alternative which benefits sugarcane handling is the double spacing between sugarcane rows—arranged to reduce the number of rows for traffic and compaction risks. In addition, using double spacing between sugarcane rows allows to plant a larger amount of plants per unit area, which may generate higher productivity.

However, it is necessary to quantify and model both the mechanical and structural behavior of the soil in order to assess the efficiency of the above-mentioned techniques. These attributes include soil compressibility providing information on two other indicators: preconsolidation pressure—reflecting the maximum load value received by the soil without additional compaction—and compression index, represented by a decrease in soil void ratio regarding stress changes along the virgin compression line and indicating the higher or lower soil susceptibility to compaction (Assis and Lanças 2005; Ajayi et al. 2009; Silva et al. 2010).

According to Lima et al. (2015), the most important soil compressibility variable is precompression stress; its relationship with the soil water content enabled to achieve load-bearing capacity (LBC), which indicates the maximum pressure that a soil can withstand at a given water content with no increase in soil compaction (Taylor 1948; Dias Júnior and Pierce 1995; Souza et al. 2012). A scenario in which contact pressure of wheelsets exceeds soil load-bearing capacity leads to a non-recoverable structural degradation (Silva et al. 2009; Vischi Filho et al. 2015); therefore, to define the load-bearing capacity of a given soil, management strategies should be defined to apply pressures below the preconsolidation pressure in order to avoid soil structural degradation (Souza et al. 2012).

In this context, our study supports the hypothesis that using autopilot provides the plant-row region with less soil compaction and improves root development. Therefore, our goal was to assess the benefits of traffic control in sugarcane cultivation areas by using load-bearing capacity modeling and developing root system.

Materials and Methods

Description of the Study Area

We carried out the experiment between May 2012 and November 2014 at an experimental sugarcane cultivation area located in the dependencies of Santa Fé Mill, region of Nova Europa, São Paulo, Brazil (latitude 21°48′29.18″S, longitude 48°37′0.54″W) (Fig. 1). It has a tropical climate with a dry season according to Köppen classification. Figure 2 shows the mean monthly temperature and rainfall throughout the experimental period.

Experimental design consisted of a randomized block with four replicates. Experimental area soil was classified as Neossolo Quartzarênico according to the Brazilian Soil Classification System (Embrapa 2013) corresponding to Entisols Quartzipsamments in Soil Taxonomy (Soil Survey Staff 2014). Table 1 shows the texture composition of the experimental soil area.

Based on the use of autopilot and different spacing distances, we implemented three different treatments in the studied area: $T1$ = sugarcane planted with row spacing of 1.50 m (simple spacing between sugarcane rows) managed without autopilot; $T2$ = sugarcane planted with row spacing of 1.50 m (simple spacing between sugarcane rows) managed with autopilot; $T3$ = sugarcane planted with row spacing of 1.5 × 0.90 m (double spacing between sugarcane rows) managed with autopilot.

Data were provided by an experiment containing a randomized complete block with four replications numbering 12 experimental units. The dimensions of each experimental unit consisted of 30 × 50 m for the 20 plant rows of the treatments using a single spacing of 1.50 m and 12 double rows for the treatment with double spacing between sugarcane rows of 1.50 × 0.90 m.

The planting operation used a chopped sugarcane planter DMB, model PCP 6000, tandem axle with four low-pressure tires of 500/45 × 22.5–12 ply, with a capacity to transport six megagrams of seedlings. We used a Valtra BH 185i intercooler tractor to perform the reaction with front and rear gauge of 2.10 and 1.80 m, respectively, and a weight of approximately 5445 kg.

Our team installed the experiment in May 2012; the first harvest occurred in November 2013 and the second in November 2014 using sugarcane variety RB 86-7515. Soil sampling was performed after the sugarcane harvest of both cane plant and first ratoon cane—using harvesters CASE model 8000 with a mass of approximately 15 megagrams adapted according to each spacing.

Soil Sampling Protocol

Undisturbed soil samples (specimen) were collected using stainless steel rings with dimensions of 0.025 m in height and 0.06 m in diameter at layers of 0.00–0.15 and 0.15–0.30 m. Sampling involved inter-row center and seedbed regions. Fifteen soil samples were collected in the inter-row center to develop the model and five samples in the seedbed region per treatment, numbering 120 samples (Fig. 3). After collection

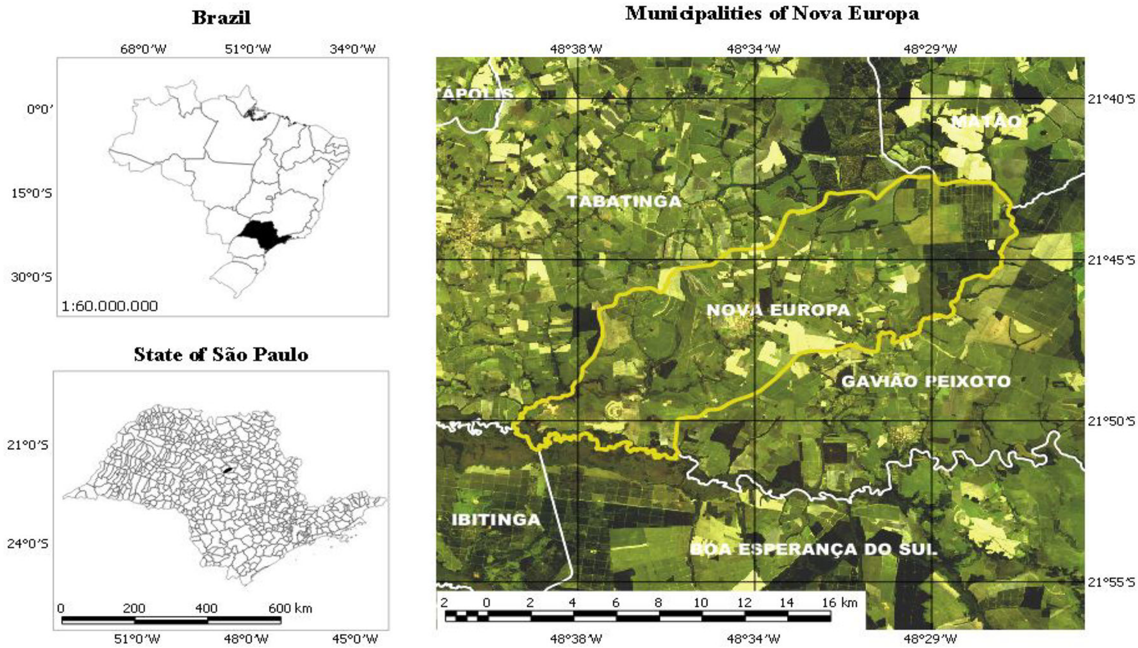

Fig. 1 Location of the municipality of Nova Europa in relation to the state of São Paulo, Brazil

Fig. 2 Mean monthly temperatures (T) and rainfall (R) occurred in the period corresponding to the experiment with the respective soil sampling time periods

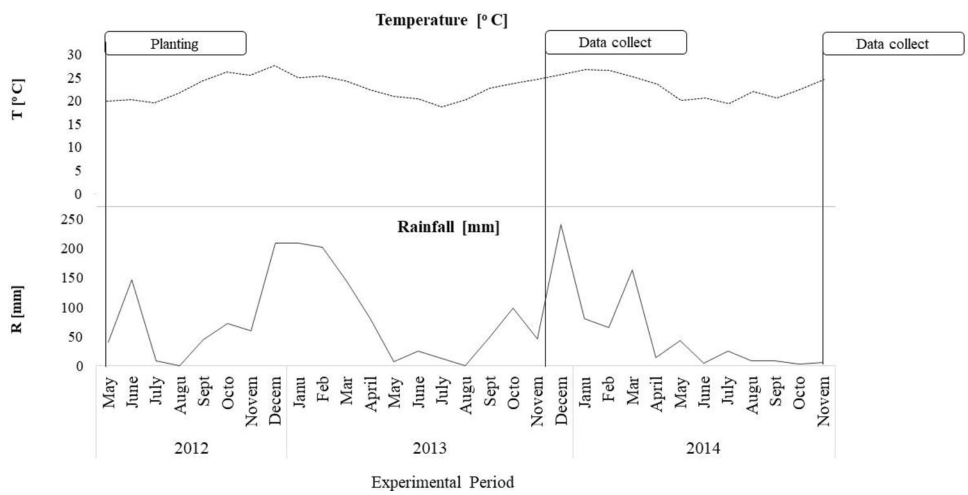

Table 1 Soil texture composition of the experimental area according to the Brazilian Society of Soil Science (Medina, 1975)

Layers (m)	CS (g kg^{-1})	FS	TS	Silt	Clay	Texture
0.00–0.10	400.50	440.15	840.65	79.00	80.35	Sand loam
0.10–0.20	420.90	390.84	811.74	107.36	80.90	Sand loam
0.20–0.30	480.30	380.02	860.32	89.50	50.18	Sand loam

CS coarse sand, *FS* fine sand, *TS* total sand

of soil samples, they were packed in foil, identified, and taken to the laboratory for analysis procedure.

The autopilot efficiency at sampling soil from plant rows is only sufficiently established by assessing soil load-bearing capacity at the point located in the seedbed region because of its location between the plant rows. Therefore, if autopilot reduces soil compaction in the seedbed region, plant rows will also be preserved (Fig. 3). In addition, deviations occurring along the tractor trajectory during the treatment without autopilot will probably not arise in the plant-rows

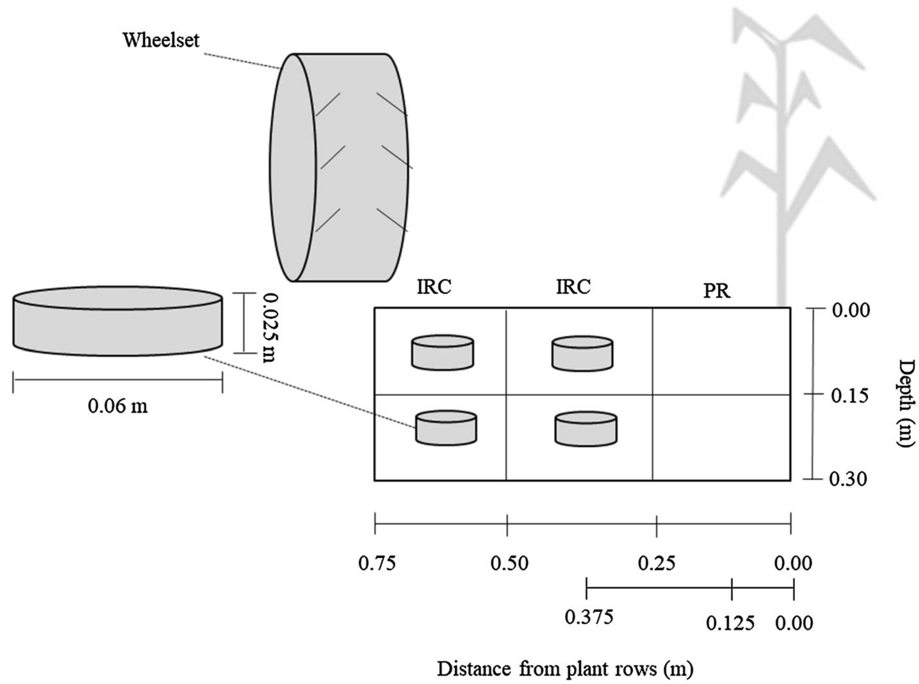

Fig. 3 Demonstration of the trench used to collect undisturbed soil samples in *IRC* inter-row center and *SR* seedbed region

region since it works to guide the machine operator; thus, it is the seedbed region which reflects traffic diversion effects.

Determination of Soil Load-Bearing Capacity and Data Analysis

The undisturbed soil samples were saturated and subsequently naturally air-dried to reach a wide moisture range from dry to saturated soil by simulating extreme field moisture conditions (Silva et al. 2009). The soil water contents used were as follows: 0.05, 0.10, 0.15, 0.20 $m^3\ m^{-3}$ and saturated soil moisture.

Preconsolidation pressure was quantified using uniaxial test and applying loads of 25, 50, 100, 200, 400, 800, and 1600 kPa (Bowles 1986) in undeformed samples. Each pressure remained until the sample reached 90% of the maximum deformation (Taylor 1971).

Uniaxial compression tests and maximum deformation control were performed according to Taylor (1971) by using an automatic consolidometer, model CNTA-IHM/BR-001/07, powered by Linker® software (Silva et al. 2014). Each pressure applied had deformation measurements of samples collected with pressure transducers and vertical displacement incorporated into the equipment and recorded using a sensor with automated data acquisition.

Estimation of preconsolidation pressure from compression curves (soil bulk density vs. pressure) followed the methodology proposed by Dias Júnior and Pierce (1995). Load-bearing capacity was estimated from the compression curve at different levels of water by Dias Junior (1994) (Eq. 1):

$$\sigma p = 10^{(a+b*\theta)}, \quad (1)$$

where σp is preconsolidation pressure of the soil (kPa), a and b equation coefficients, and θ soil water content ($m^3\ m^{-3}$).

We developed a model for each soil layer in both crop cycles—cane plant and first ratoon cane—using 15 samples collected from the inter-row center, the region with the highest soil load-bearing capacity. Subsequently, 15 samples were collected from the seedbed region per treatment and graphically plotted to validate the model corresponding to its layer and cycle, according to Fig. 4.

For data interpretation, regions “a” and “c” were considered as the locations with the highest preconsolidation and the lowest load-bearing capacity values, respectively, against the confidence interval differently from the model. Any point in region “b” corresponds to load-bearing capacity values

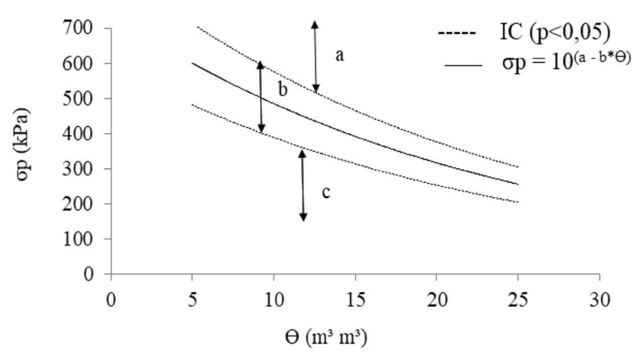

Fig. 4 Limits of the confidence interval (CI) of the soil load-bearing capacity mathematical model with $p < 0.05$ probability (Dias Júnior et al. 2005; Thebaldi et al. 2012)

statistically equal to the points in the inter-row and can be represented in the model at 5% probability. Confidence interval was determined according to Equation CI.

$$\mathrm{CI} = M \pm t\frac{\mathrm{SD}}{\sqrt{n}}, \quad (2)$$

where CI is confidence interval, M average of values, t tabulated value of the t-Student distribution, SD standard deviation, and n number of samples.

Determination of Root System Development and Data Analysis

The root system assessment used images obtained from CI-600 (BioScience)—similar to a scanner—consisting of a visualization probe and an acrylic tube to access and capture images inside the soil. Each experimental unit had three tubes installed in the inter-row center and seedbed region of plant rows. Image capturing occurred on the soil surface at a depth of 0.40 m (Fig. 5).

The assessments were followed by an image treatment with CI-960 RootSnap computer system (CID Bio-Science. Inc., Camas. Washington. USA) to establish the root area. The root system analysis encompassed a descriptive analysis of the root area using distribution maps on Surfer 9.0 software.

Data Analysis

Data were submitted to variance analysis and a Tukey test ($p < 0.05$) establishing a comparison of means through Sisvar computational system, version 5.1 (Ferreira 2011).

Results and Discussion

Table 2 illustrates mathematical models and soil load-bearing capacity confidence intervals for each moisture analyzed. Coefficient "b" negative values found in all load-bearing capacity models in the inter-row center region suggest a negative relationship between this variable and soil moisture. Increased moisture decreases cohesion by altering the friction angle between the particles (clay, silt, and sand), which facilitates the accommodation and reduction of porous space resulting from the loads applied. This scenario reveals that uniaxial tests reproduce the wheel effect in field conditions. (Pacheco and Cantalice. 2011; Souza et al. 2012; Silva et al. 2014; Visch Filho et al., 2015).

Particle arrangement is facilitated by the lubricating effect derived from water film enveloped in the soil solids, responsible for reducing the cohesion between the bodies and consequently decreasing load-bearing capacity (Silva et al. 2009). Thus, increased moisture makes the soil more vulnerable to compaction, especially at traffic. According to Braga et al. (2015), high humidity reduces load-bearing capacity since this condition leads the soil to acquire a plastic (semisolid) state, susceptible to large non-recoverable deformations (plastic), and significantly increases compaction risk when these soils are trafficked by machines or trampled by animals.

Figure 6 shows the load-bearing capacity models generated with the samples collected in the inter-row center and the limits of the confidence interval ($p < 0.05$). The points collected in the seedbed region of each treatment

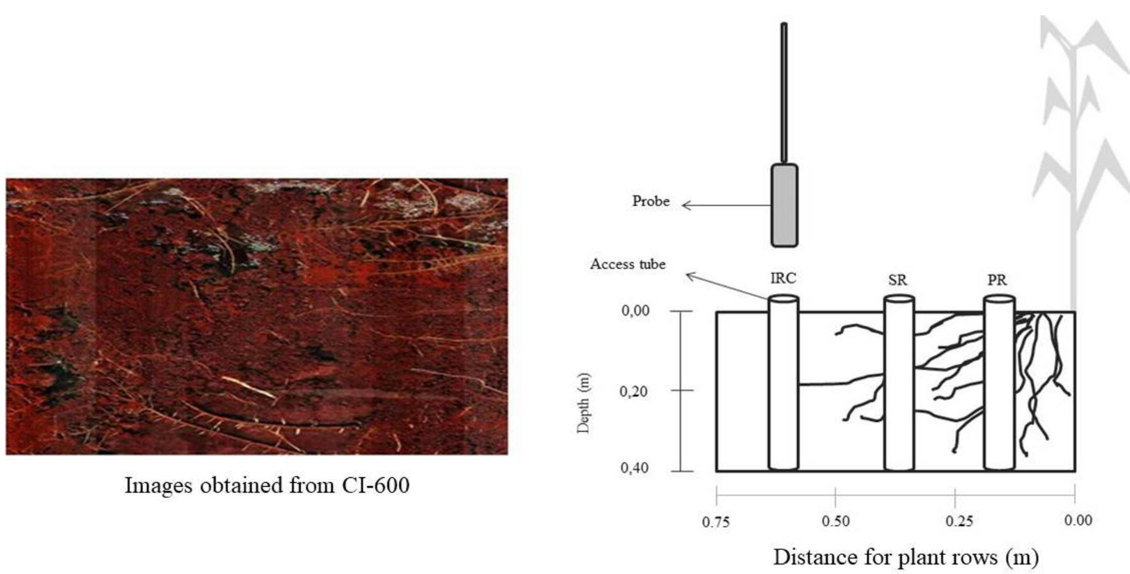

Fig. 5 Demonstration of the root image captured through the probe CI-600 and location of the access tubes. *IRC* inter-row center, *SR* seedbed region, and *PR* plant rows

Table 2 Mathematical models and confidence intervals of the load-bearing capacity at the inter-row center point of a typic Entisols Quartzipsamment cultivated with sugarcane

Cycle	Layer (m)	Models	θ (m^3 m^{-3})				
			0.05	0.10	0.15	0.20	Saturated
Cane plant	0.00–0.15	$\sigma p = 10^{(3.10-0.52\theta)}$	± 183.37	± 79.96	± 12.25	± 113.09	± 38.24
	0.15–0.30	$\sigma p = 10^{(3.15-0.54\theta)}$	± 56.50	± 210.88	± 133.75	± 68.05	± 70.89
First ratoon cane	0.00–0.15	$\sigma p = 10^{(3.16-0.51\theta)}$	± 75.85	± 69.95	± 156.17	± 60.25	± 26.79
	0.15–0.30	$\sigma p = 10^{(3.15-0.48\theta)}$	± 4.97	± 219.86	± 169.66	± 135.39	± 78.25

σp preconsolidation pressure of the soil (kPa), *θ* soil water content (m^3 m^{-3})

were plotted to validate the model corresponding to its soil layer and year of assessment.

According to both assessment strata, load-bearing capacity values in the seedbed region of all treatments occurred at the lower portion of the models found in the inter-row center regarding both assessment cycles (Fig. 6). We verified such behavior for all moisture levels analyzed, which occurred due to higher traffic intensity in the inter-row center. These results corroborate with Roque et al. (2011) and Souza et al. (2012), who verified that the traffic

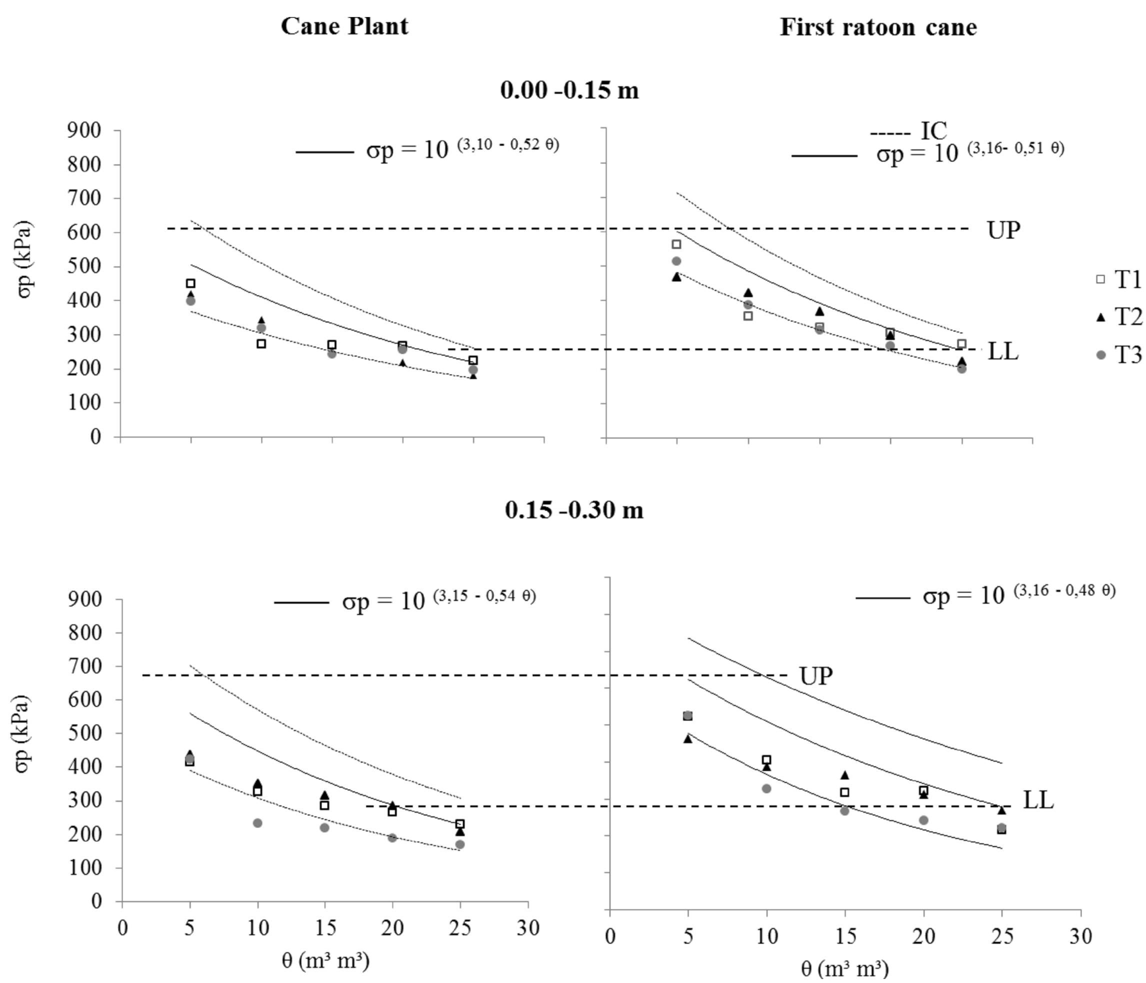

Fig. 6 Soil load-bearing capacity (*σp*) in the region of the inter-row center point of a Entisols Quartzipsamments cultivated with sugarcane. *IC* = confidence Interval, *T1* = sugarcane planted with row spacing of 1.50 m (single spacing between rows) and managed without autopilot, *T2* = sugarcane planted with row spacing of 1.50 m (single spacing between rows) and managed with autopilot, *T3* = sugarcane planted with row spacing of 1.5 × 0.90 m (double spacing between rows) and managed with autopilot. *UP* upper limit of mathematical model, *LL* lower limit of mathematical model

of machines in sugarcane areas provides additional soil compaction, especially in the inter-row center, promoting higher contact between particles and reducing total soil porosity.

In the layer 0.00–0.15 m of the sugarcane-plant cycle, only the treatment without autopilot (moisture of 0.10 m^3 m^3) presented load-bearing capacity outside the confidence interval limit (Fig. 6). This result shows a lower load-bearing capacity in relation to the remaining treatments, which had values within the confidence interval ($p < 0.05$)—equal to the values found in the inter-row center. Despite all load-bearing capacity values in the seedbed region within the confidence interval, we found in the layer 0.00–0.15 m of the first ratoon cane cycle that treatments with controlled traffic were closer to the values of lower limit of the interval and confidence, which demonstrates less traffic influence in the seedbed region of the treatments with autopilot and better preservation of soil structure in the region with plant growth.

These results contradict our previous expectations of higher load-bearing capacity values for all points collected in the seedbed region of the treatment without controlled traffic in relation to the remaining treatments (Fig. 6). According to Silva et al. (2006), soil tillage stage occurred similarly to all remaining treatments and was characterized through intense soil rotation, which may have provided load-bearing capacity homogenization of the layers studied. In addition, the low structure of Entisols Quartzipsamments attributed to a high sand percentage and short application period of the treatments leads to considerable changes.

At layer 0.15–0.30, in both crop cycles—cane plant and first ratoon cane—the seedbed region of the double spacing between rows and autopilot treatment presented values below the confidence interval for moistures of 0.10. and 0.15 m^3 m^3, which may have occurred due to reduced machine deviations provided through the automatic pilot (Fig. 6). This result proves that machine traffic guided by the autopilot can contribute to preserve soil structure and provide the plants with better development.

These results are in agreement with Souza et al. (2012), who found that the traffic control of machines in a sugarcane area reduced the load-bearing capacity of a Rhodic Hapludox in the plant rows at layers 0.00–0.15 and 0.15–0.30 m. We did not carry out any assessment on the plant rows for having considered that when the soil structure in the seedbed region is preserved, the results are extended to plant rows.

We emphasize an increase in the upper and lower limits of the soil load-bearing capacity models in the first ratoon cane in relation to cane plant, which increased from 9 to 18% in the first layer for the upper and lower limits, respectively, and from 19% for the upper limit to 33% for the lower limit in the layer of 0.15–0.30 m. These results corroborate Pacheco and Cantalice (2011), who stated that with the course of sugarcane cultivation cycles, soil degradation occurs with increases in soil load-bearing capacity.

Furthermore, it is important to discuss that despite the close proximity between the load-bearing capacity values of the seedbed region in the treatments studied, treatment T3 (using double spacing) reduced the number of rows destined to traffic. Double spacing 1.50 × 0.90 m. replacing the single spacing of 1.50 m. reduced from 20 to 12.5 the number of rows in the traffic. In addition, we highlight the absence between double rows of traffic interference and the a better preservation of the soil structure, which can contribute to plant growth.

For the next cycles of sugarcane cultivation, we expect all treatments to show increased load-bearing capacity in the seedbed region since it is closer to the traffic lines, especially for the treatment without autopilot guidance. This hypothesis is based on the results found in a three-year study by Visch Filho et al. (2015), who found higher values of load-bearing capacity in a Rhodic Hapludox cultivated with mechanized sugarcane in relation to an area containing only one cycle.

The root system of the sugarcane crop showed a decreasing distribution of plant rows for the inter-row center with higher concentration at the first layers along the two years of assessment. This result corroborates with Chopart et al. (2010), Sousa et al. (2013), and Souza et al. (2015) (Fig. 7).

In the final period corresponding to the cane-plant cycle, the root system presented higher distribution, including at the transit region for a center between rows, a behavior which may have been influenced by the short traffic period in the area providing the soil with lower load-bearing capacity and the root growth with lower resistance in relation to the first ratoon cane cycle (Fig. 7).

However, in the end of the first ratoon cane for the treatment with controlled traffic, especially regarding the treatment with double spacing, the root system presented greater distribution in the plant rows because of lower traffic intensity at these points in relation to the treatment without autopilot guidance. These results show that controlled machine traffic provides soil preservation, especially in regions with root growth, which may contribute to the increase of sugarcane productivity since the set of roots will have lower resistance to absorption of water and nutrients.

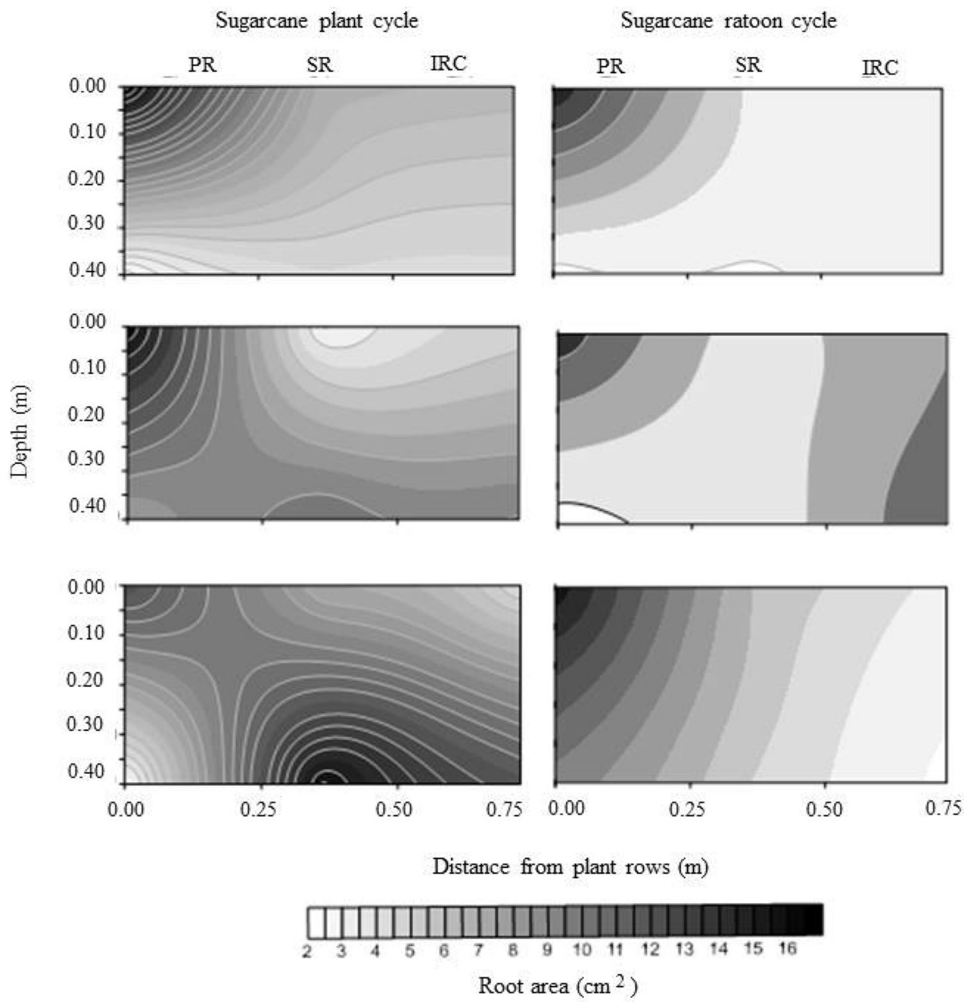

Fig. 7 Distribution of the root system of the sugarcane culture over different managements, *T*1 = sugarcane planted with row spacing of 1.50 m (single spacing between rows) and managed without autopilot, *T*2 = sugarcane planted with row spacing of 1.50 m (single spacing between rows) and managed with autopilot, *T*3 = sugarcane planted with row spacing of 1.5 × 0.90 m (double spacing between rows) and managed with autopilot. *IRC* inter-row center, *SR* seedbed region, and *PR* plant rows

Conclusion

The use of autopilot in the seedbed area is less influenced by machine traffic, which guarantees preserved soil structure maintenance in the plant row region.

Additionally, load-bearing capacity increases as the sugarcane cultivation cycles evolve, including higher soil load-bearing capacity at the first ratoon cane cycle in relation to the cane-plant cycle.

The sugarcane crop root system has good distribution during the cane-plant cycle; however, the first ratoon cane cycle has a downward trend regarding plant rows in the inter-row center because of intensive machine traffic.

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