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Sugarcane root system: Variation over three cycles under different soil tillage systems and cover crops

Lenon Henrique Lovera[a,*], Zigomar Menezes de Souza[b], Diego Alexander Aguilera Esteban[a], Ingrid Nehmi de Oliveira[a], Camila Viana Vieira Farhate[a], Elizeu de Souza Lima[a], Alan Rodrigo Panosso[c]

[a] Postgraduate Program in Agricultural Engineering, University of Campinas (UNICAMP), School of Agricultural Engineering (FEAGRI), Av. Cândido Rondon, 508, Campinas, SP, 13083-875, Brazil

[b] University of Campinas (UNICAMP), School of Agricultural Engineering (FEAGRI), Department of Water and Soils, Av. Cândido Rondon, 508, Campinas, SP, 13083-875, Brazil

[c] Department of Exact Sciences, São Paulo State University, FCAV/UNE SP, Via De Acesso Prof. Paulo Donato Castellane s/n, 14884-900 Jaboticabal, SP, Brazil

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ABSTRACT

Machinery traffic combined with soil management processes in the establishment of sugarcane areas degrades the soil structure, limiting root development and yield of the crop. The use of conservation tillage systems and cover crops can reduce such effects and improve its soil physical quality. Therefore, a field study was conducted over three agricultural years to assess the development of the sugarcane root system planted under different soil tillage systems and cover crops during three crop cycles. The study was carried out in 2014 in Ibitinga (São Paulo, Brazil) in an experimental design in split-plot scheme, with three repetitions and three soil tillage systems (no-tillage, minimum tillage and minimum tillage with deep subsoiling) combined with four cover crops (sorghum, millet, peanut and sunn hemp), plus one control treatment consisting of conventional tillage and no cover crop use. The root system attributes (dry biomass, density, volume, length, and surface area) were evaluated every three months during the 2015/2016, 2016/2017, 2017/2018 crop years, in the 0.0−0.2 m, 0.2−0.4 m and 0.4−0.6 m layers. Although few significant differences were obtained in the root system of the sugarcane between the different soil tillage systems and use of cover plants, the accumulation of roots was evidenced during the second cycle of the crop, mainly due to the contribution of new roots, arising from the ratoons of the plants. Differences in the dry biomass of the roots were obtained in the minimum and minimum tillage with deep subsoiling, only at the time of harvesting the first crop cycle (cane plant, 395 days after planting) and in the second cycle, 665 days after planting. The highest concentration of root dry biomass was obtained in the 0.0−0.2 m surface layer, containing between 36 % and 62 % of roots. However, the significant differences of root dry biomass between the soil tillage and cover crops occur in the clayey layer at 0.30−0.6 m, where the management effects affected the root system. During the first three sugarcane cycles, the 0.0−0.2 m surface layer concentrated the highest amount of dry biomass of the roots, representing between 36 % and 62 % of the roots present in the first 0.6 m deep.

1. Introduction

The crop's production cycles, which last on average five to six harvests, cause changes to the sugarcane root system over time, as the effects of soil tillage, crop management, mechanized operations and climate can affect its development, ultimately resulting in crop yield changes (Aquino et al., 2015). As a result, sugarcane production has fallen in recent years, a trend related to increased mechanized harvesting, resulting in high levels of soil compaction, which consequently reduce root growth (Rossi Neto et al., 2018; Esteban et al., 2019). Brazil is currently the world leader in sugarcane production, reaching 620.4 million Mg year^{-1} in the 2018−19 crop year in an area of 8.59 million hectares, and estimates for the 2019/2020 crop year are 615.9 million Mg year^{-1}. The average yield for the 2019/2020 crop year should

* Corresponding author.
E-mail address: lhlovera@gmail.com (L.H. Lovera).

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increase by 1.6 %, from 72.2 Mg ha^{-1} to 73.4 Mg ha^{-1} (CONAB, 2019).

The use of farming implements in soil tillage for sugarcane production alters the soil structure, increasing compaction (Bordonal et al., 2018a). An effective alternative to improve soil quality and increase production sustainability is the use of cover crops during the planting period (Barbosa et al., 2018). The benefits of using cover crops include protecting the soil surface (Ambrosano et al., 2013) and reducing the load of agricultural machinery (Debiasi et al., 2008), resulting in increasing nutrient availability and controlling the development of weeds, diseases, nematodes and pests (Castro et al., 2011), which can directly benefit succeeding crops.

In general, the larger the root system of a plant, the greater its ability to exploit the soil. However, the number of roots is not the determining factor of good production, but rather its distribution over the soil profile during its cycle (Faroni and Trivelin, 2006). Baquero et al. (2012) observed a reduction in sugarcane root development below 0.10 m caused by impeding soil physical conditions, associated with soil compaction. According to Vasconcelos et al. (2003), sugarcane has 70 % of root dry mass up to 0.40 m deep, which is the layer most impacted by machinery traffic (Severiano et al., 2010). It is essential for the development of crops that the soil present favorable conditions for root growth, which enables them to exploit a greater volume of soil and reach greater depth, increasing access to water and reducing the risks of water deficiency (Kaiser et al., 2009; Esteban et al., 2019), thus allowing the crop to produce to its full potential.

Root growth depends on the crop variety, the physical, chemical and biological parameters of soil quality and the crop management system (Vasconcelos et al., 2003), also its distribution in the soil profile can provide useful information for water management, since the greater the actual rooting depth, the better the roots benefit from water and nutrients, besides withstanding water stress and, consequently, increasing yield (Ohashi et al., 2015; Moraes et al., 2018). At the end of the cane plant cycle, sprouting roots are superficial, since, in root development, secondary roots occur after elongation growth, which occurred at the beginning of the cycle (Smith et al., 2005). Consequently, over cycles, the greater the possibility of the root system being located superficially throughout the cycles (Alvarez et al., 2000).

With this, it is clear that the root system is of paramount importance for sugarcane, but there are scant studies analyzing its root system during the cycles and which can help us understand its behavior over time, as it is directly affected by the amount of water in its different phenological phases (Oliveira et al., 2019) or due to resistance to penetration (Barbosa et al., 2018). The use of soil tillage systems may alleviate the problem, increasing the yield of crops, their infiltration and water storage, root depth, and subsequent water and nutrient uptake (Mazurana et al., 2011).

Information on sugarcane root development over more than one crop cycle and under conservation management systems is poorly known and scarce in the literature due to difficulties of assessment and the high number of assessment steps. Given this context, the authors decided to innovate in evaluating the evolution of the root system, using various treatments to verify the effect of soil tillage systems and cover crops on the sugarcane root system over time. This study hypothesized that conservation tillage systems combined with the use of cover crops allow greater sugarcane root development over three crop cycles, compared to the conventional tillage system with no cover crops. To test this hypothesis, the objective of this study was to evaluate the development of the root system of sugarcane planted under different soil tillage systems and using cover crops during three cycles.

2. Material and methods

2.1. Experiment area

The experiment was carried out in the field at the Santa Fé mill, located at 21°46′ S and 48°33′ W, altitude 490 m, in the municipality of Ibitinga (São Paulo, Brazil). The region's climate is classified as tropical with dry season (Aw) according to the Köppen and Geinge system (Alvares et al., 2013), cold and dry in winter, and hot and rainy in summer. The average annual rainfall and relative temperature in the region are around 1260 mm and 22.9 °C, respectively (Cepagri, 2018).

The soil was classified as *Argissolo Vermelho distrófico típico* according to the Brazilian Soil Classification System () and as Ultisol Udult Typic Hapludults according to the Soil Taxonomy System (Soil Survey Staff, 2014), with a moderate surface A horizon, a B textural subsurface horizon, and a slightly undulating relief. Table 1 shows the physical and chemical attributes of the soil obtained at the end of the cane plant cycle, when the root system samples were initially collected, for characterization. The chemical attributes were determined according to Raij et al. (2001) and the particle-size distribution and physical attributes according to Teixeira et al. (2017).

2.2. Treatments

The experiment was implemented in 2015 as plots subdivided into rows with three repetitions. In the experimental plots, measuring 10 m wide by 30 m long, 6 sugarcane rows were planted parallel to the length of the plot with 1.5 m inter-row centers. The soil tillage systems were combined with cover crops. The cover crops used were: i) SH – sunn hemp (*Crotalaria juncea*) IAC KR1 variety; ii) MI - millet (*Pennisetum glaucum* L.) BRS 1501 variety; iii) PE - peanut (*Arachis hypogaea* L.) Runner IAC 886 variety; iv) SO - sorghum (*Sorghum bicolor* L.) BD 7607 variety. The soil tillage systems used were: i) MT - minimum tillage with subsoiling at 0.4 m; ii) MT/DS - minimum tillage with deep subsoiling at 0.7 m; iii) NT - no-tillage, i.e., no soil tillage was done before planting the sugarcane. An additional control system was implemented, consisting of conventional tillage (CT) for sugarcane areas, i.e., with no cover crops and conventional tillage using two light harrowings.

2.3. Experiment execution

Before the implementation of the experiment, the study area had been cultivated with pasture for 11 years, and, in December 2014, there was a process of land-use change to sugarcane. The chronological order of events in the study area is shown in Fig. 1. In the process of changing from pasture to sugarcane, 2.0 Mg ha^{-1} of dolomitic limestone (85 % of PRNT) were applied, incorporated with a plowing grid up to 0.4 m deep, followed by a leveling grid at 0.2 m deep.

The establishment of the experiment started in December 2014 with the characterization of the area and the elimination of pasture. Subsequently, in the same month, the cover crops were planted. Sunn hemp (25 kg ha^{-1} of seeds) and sorghum (10 kg ha^{-1} of seeds) were sown in rows using a nine-row no-till seeder, and peanut (110 kg ha^{-1} of seeds) was sown using a four-row seeder. The seeders were pulled by a Valtra BM 125i tractor (98 kW of power and mass of 7.92 Mg). Millet (18 kg ha^{-1} of seeds) was sown using a manual furrow due to the small size of the seed.

In March 2015, when the cover crops reached maximum flowering (the period with highest phytomass accumulation), sampling was performed for analysis of dry biomass (DB) in an area of 2.0 m^2 in each plot. Subsequently, the biomass was dried in an oven at 65 °C for 72 h, resulting in 11 Mg ha^{-1}, 10 Mg ha^{-1}, 5 Mg ha^{-1}, and 21 Mg ha^{-1} for sunn hemp, millet, peanut, and sorghum, respectively. After sampling, the sunn hemp, millet and sorghum crops were desiccated by applying 200 L ha^{-1} of syrup composed of 6.0 L ha^{-1} of a commercial product based on the active ingredient (ai) glyphosate +70 mL ha^{-1} carfentrazone-ethyl (commercial product based on the ai) + 1.0 L ha^{-1} of mineral oil, followed by mechanical management using a knife roller. The peanut crop was harvested using a Massey Ferguson 7140 tractor (104 kW of power and mass of 7.70 Mg) and a Double Master harvester.

The sugarcane crop (CTC4 variety) was planted on April 17, 2015, using a DMB chopped sugarcane planter pulled by a John Deere tractor.

Table 1
Characterization of Ultisol Udult Typic Hapludults obtained at the end of the cane plant cycle of the experiment in the municipality of Ibitinga-SP, Brazil.

Layer (m)	*Physical attributes* Ds Mg m^{-3}	Macro m^3 m^{-3}	Micro	TP	RP MPa	*Particle-size distribution* Sand g kg^{-1}	Silt	Clay	Textural class[a]
0.0–0.1	1.54	0.16	0.24	0.40	0.74	743	96	160	Sandy loam
0.1–0.2	1.66	0.11	0.25	0.36	1.19	768	87	145	Sandy loam
0.2–0.3	1.67	0.10	0.25	0.35	1.32	723	87	189	Sandy loam
0.3–0.6	1.60	0.07	0.30	0.37	1.45	651	90	260	Sandy clay loam

	Chemical attributes P mg dm^{-3}	Ca^{2+} cmol$_c$ dm^{-3}	Mg^{2+}	K^+	m	pH
0.0–0.1	4.66	146	0.75	0.14	0.45	521
0.1–0.2	2.54	1.07	0.64	0.07	0.90	4.91
0.2–0.3	1,9	1.05	0.60	0.05	1.21	4.73
0.3–0.6	142	099	0.63	0.04	1.23	474

[a] Classification established by the United States Department of Agriculture (United States Department of Agriculture (USDA) et al., 2017). Ds = soil density; Macro = macroporosity; Micro = microporosity; TP = total porosity; RP = soil resistance to penetration; pH = potential hydrogen ($CaCl_2$); P = available phosphorus content; Ca^{2+} = exchangeable calcium content; Mg^{2+} = exchangeable magnesium content; K^+ = exchangeable potassium content; m = potential acidity.

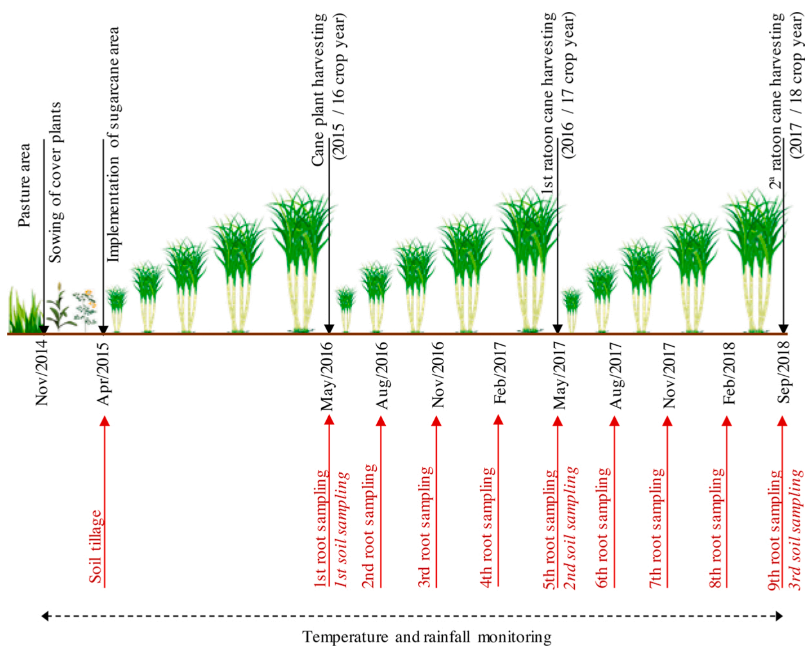

Fig. 1. Chronology of experiment execution in the study area at the Santa Fé mill in the municipality of Ibitinga (São Paulo, Brazil).

Fertilization consisted of 300 kg ha^{-1} of N-P-K (10-51-00). In the plots without cover crops (CC), soil tillage was done with two light harrowings using a Baldan 36-disc hydraulic harrow and a Case MXM 200 hp tractor. In addition, the MT and MT/DS systems were implemented using an Ast-Matic 550 5-shank subsoiler, reaching depths of 0.4 m and 0.7 m, respectively.

Mechanized sugarcane harvesting was carried out in May 2016 (2015/2016 crop year, cane plant production cycle), in May 2017 (2016/2017 crop year, first ratoon cane production cycle) and in September 2018 (2017/2018 crop year, second ratoon cane production cycle), using a John Deere 3520 harvester with track chains. The mechanized operations carried out in each treatment and traffic intensity are shown in Fig. 2. During the execution of the experiment, rainfall and average temperature were monitored using a DRIA-0111 automatic surface weather station installed in the area. Sugarcane yields for the 15/16, 16/17 and 17/18 cycles are shown in Table 2.

2.4. Root system assessment

The root system was assessed every three months using the methodology described by Otto et al. (2009). Stainless steel probes measuring 1.0 m long and 5.5 cm in internal diameter (SONDATERRA®) were used to collect soil samples at depths of 0.0–0.2 m, 0.2–0.4 m, and 0.4–0.6 m, at sites in the planting rows (A), seedbed areas (B) and inter-row centers (C) (Fig. 3).

The assessments were performed from the first cane plant harvesting, occurring at the following times: 395 days after planting (DAP) = 1st sampling, at the time of cane plant harvesting (May/2016); 485 DAP = 2nd sampling, 90 days after cane plant harvesting (August/2016); 575 DAP = 3rd sampling, 180 days after cane plant harvesting (November/2016); 665 DAP = 4th sampling, 270 days after cane plant harvesting (February/2017); 755 DAP = 5th sampling, first ratoon cane harvesting (May/2017); 845 DAP = 6th sampling, 90 days after first ratoon cane harvesting (August/2017); 935 DAP = 7th sampling, 180 days after first ratoon cane harvesting (November 2017); 1025 DAP = 8th sampling,

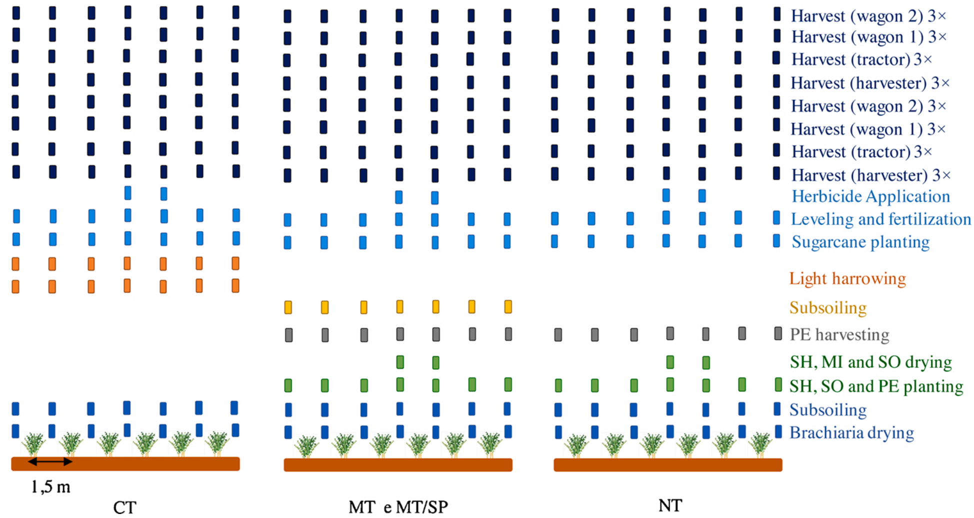

Fig. 2. Mechanized operations and number of passages of machine tires (front and rear tires) in inter-row centers of the sugarcane area in the different treatments of the experiment. CT = conventional tillage without cover crops; MT = minimum tillage with subsoiling at 0.4 m; MT/DS = minimum tillage with deep subsoiling at 0.7 m; NT = no-tillage; SH = sunn hemp; SO: sorghum; PE = peanut; MI: millet; 3 × = operation performed three times, once for each crop cycle.

Table 2
ugarcane yield in the 2015/2016, 2016/2017 and 2017/2018 cycles.

Sugarcane yield (Mg ha^{-1})												
Treatment / Cover Crop	*Plant cycle (2015/2016)*				*First ratoon cane (2016/2017)*				*Second ratoon cane (2017/2018)*			
	NT	MT	MT/DS	Mean	NT	MT	MT/DS	Mean	NT	MT	MT/DS	Mean
Peanut	106	110	104	106A	102	99	102	100A	113	106	96	105A
Sunn hemp	117	102	116	111A	104	99	114	105A	116	88	94	99.3A
Millet	113	100	110	107A	106	99	103	102A	97	95	97	96.3A
Sorghum	101	109	119	109A	97	108	108	104A	96	99	99	98A
Mean	109a	105a	112a		101a	101a	106a		105a	97a	96.5a	
CT	105				104				98			

CT = conventional tillage, MT/DS = minimum tillage with deep subsoiling, MT = minimum tillage, NT = no-tillage. Means followed by the same letter, uppercase in the column and lowercase in the row, do not differ from each other by Tukey's test ($p < 0.05$).

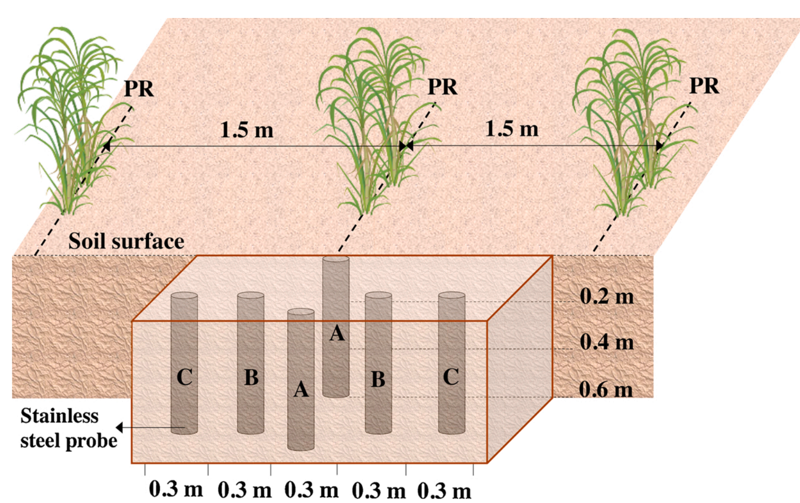

Fig. 3. Sampling scheme for the assessment of the sugarcane root system using probes up to depths of 0.6 m. PR = Planting row; A, B and C = root sampling sites.

270 days after first ratoon cane harvesting (February/2018); 1200 DAP = 9th sampling, second ratoon cane harvesting (September/2018).

The roots were washed in running water and sieved with a 2.0-mm mesh to eliminate soil, according to Vasconcelos et al. (2003). The roots were digitalized using an optical scanner with a resolution of 300 dpi and the images were processed in SAFIRA® - version 1.1 (JORGE et al., 2010) software to determine total root length (TRL), root volume (RV), root surface area (RA), root diameter (rd) and root length in the diameter classes of rd <0.5 mm ($RL_{0.5}$), 0.5 mm ≤ dr ≤ 2.0 mm ($RL_{0.5-2.0}$) and dr> 2.0 mm ($RL_{2.0}$). Finally, the roots were dried in an oven with air circulation at 65 °C for 72 h to obtain the root dry mass (RDM). Root dry biomass (RDB) was calculated according to Otto et al.

(2009), as described by equation 1:

RDB = [(RD_A × (W_A/W_T) + RD_B × (W_B/W_T) + RD_C × (W_C/W_T)] × 10,000 m^2 × D (1)

in which RDB = root dry biomass (kg ha^{-1}); RD_A, RD_B and RD_C = root density (g dm^{-3}) at the sampling sites A, B and C, respectively (equation 2); W_A, W_B and W_C = width of strips (m) at the A, B and C sampling sites, respectively; W_T = width of inter-row centers (1.5 m); D = depth of soil layer (m).

RD_A, RD_B and RD_C = RDM/V (2)

in which RDM = root dry mass (g); V = volume of sample (V =0.475 dm^{-3}).

2.5. Statistical analyses

The statistics were performed using R Studio statistical software (1.1.463, R Foundation for Statistical Computing), by analysis of variance (ANOVA) using the F-test at 5 % significance level by factor analysis with additional treatment, and later using analysis by strip to compare the treatments, in which Tukey's test was applied at the 5 % probability level.

3. Results

During the execution of the experiment, maximum monthly rainfall occurred in January 2016 with 421 mm, and in January 2017 with 424 mm. The minimum indices were in June 2015, 2017, and 2018, with 4, 11, and 0 mm, respectively, besides July 2018, with 0 mm (Fig. 4). Cumulative rainfall during the cane plant cycle (0–395 DAP, 2015/2016 crop year) was 1551 mm. Cumulative rainfall in the first ratoon cane cycle (396–755 DAP, 2016/2017 crop year) was 1041 mm, while in the second ratoon cane cycle (766–1200 DAP, 2017/2018 crop year) it was 1063 mm. The monthly average temperature showed minimum values of 17 °C and 17.5 °C in June 2016 and June 2018, respectively, and a maximum value of 28 °C in February 2017. One notes that the cane plant cycle (0–395 DAP) had the largest water surplus in the hydric balance, while the second ratoon cane cycle (766–1200 DAP) showed the largest deficits. These values are in accordance with the annual rainfall of the area, where over the years there has been a decrease in rainfall (Fig. 4).

Fig. 5 features the root dry biomass (RDB) values of sugarcane for the different treatments at a depth of 0.0−0.6 m over the agricultural years assessed. In the soil tillage systems, significant differences were only found between cover crops at 395 DAP when using minimum tillage (MT) and at 665 DAP when using minimum tillage with deep subsoiling (MT/DS).

RDB was significantly higher in MT using millet (MI) and sorghum (SO) as cover crops at 395 DAP, with 1399 and 1334 kg ha^{-1}, respectively (Fig. 5). Peanut (PE) with the same tillage system resulted in the lowest sugarcane RDB, with 644 kg ha^{-1}, 54 % lower when compared to MI. Also, in this tillage system, the largest root growth occurred at 755 DAP, when ratoon cane was first harvested. In the MT/DS system, the highest sugarcane RDB was obtained when using MI as a cover plant, showing significant differences at 665 DAP with a production of 2792 kg ha^{-1} (Fig. 5). In the same tillage system with the other cover crops, SH, PE and SO accounted for RDB of 2,003, 1,953, and 1337 kg ha^{-1}, respectively.

To expand the understanding of the effects of soil management systems and cover crops on the development of the sugarcane root system, RDB was analyzed for each tillage system and cover crop in each soil layer (Table 3). In general, higher RDB was obtained in the 0.0−0.2 m surface layer, reducing with depth. However, some treatments showed a slight increase in RDB with depth, as verified in CT at 395 and 485 DAP, where there was an increase in the 0.4−0.6 m layer (23 %) compared to 0.2−0.4 m layer (20 %), and in the 0.2−0.4 m layer (41 %) compared to the 0.0−0.2 m layer (40 %), respectively.

RDB increase with depth was also observed in the 0.2−0.4 m layer compared to the 0.0−0.2 m layer at 575 and 845 DAP in the management system of MI + MT, at 755 DAP in PE + MT and NT and MI + MT/DS, at 845 DAP in SH + MT/DS, and 1025 DAP in PE + MT/DS and NT, and in SH and MI + MT/DS (Table 3). Significant differences in RDB were only found in the 0.2−0.4 m and 0.4−0.6 m layers (Table 3). The 0.2−0.4 m layer showed significant RDB differences in the samplings at 395, 665 and 1025 DAP; however, in the 0.4−0.6 m layer, significant differences were found in the samplings at 395, 575, 665, 755, 845, and 1025 DAP. One notes, therefore, that most differences occurred in the deeper soil layers.

In the 0.0−0.2 m layer there were no significant differences between treatments and the highest RDB amounts occurred in this same layer, while in the subsurface layers, the greater the differences between treatments. It is noteworthy that CT values in all layers were lower than in most of the other tillage systems, regardless of the cycle.

At 395 DAP, in the 0.0−0.2 m layer, the highest RDB was obtained using SO + MT and MT/DS, MI + MT, and peanut + NT, while the lowest RDB was found in PE + MT and MI + NT and MT/DS (Table 3). In the 0.2−0.4 m layer, the highest RDB was found in PE + NT, SO + NT, SH + MT, and SO + MT, and the lowest RDB was obtained in CT. In the 0.4−0.6 m layer, only millet showed significant differences in RDB, being higher in association with MT, followed by MT/DS and NT. In the third sampling (575 DAP), millet + MT/DS and sorghum + MT

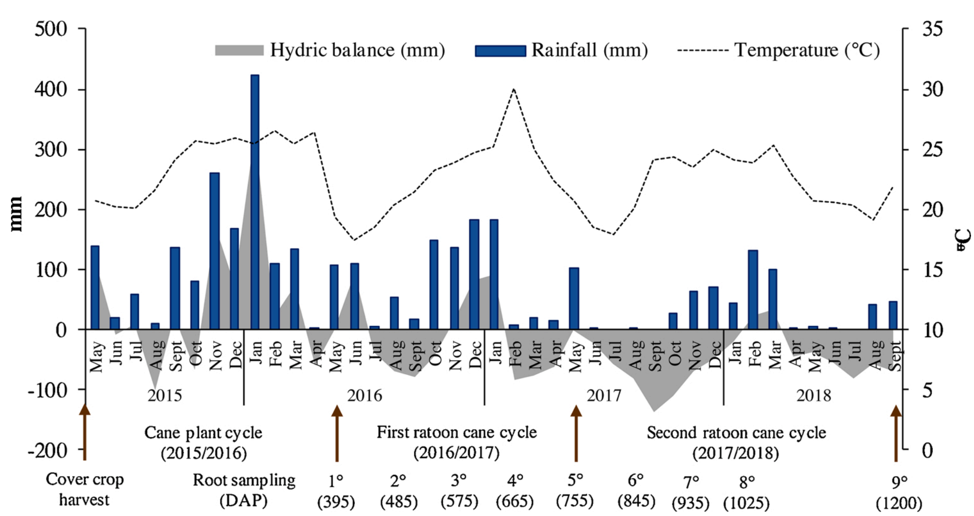

Fig. 4. Climate data during the execution of the experiment between 2015 and 2018 in the municipality of Ibitinga (São Paulo, Brazil). Values in parentheses represent days after planting (DAP).

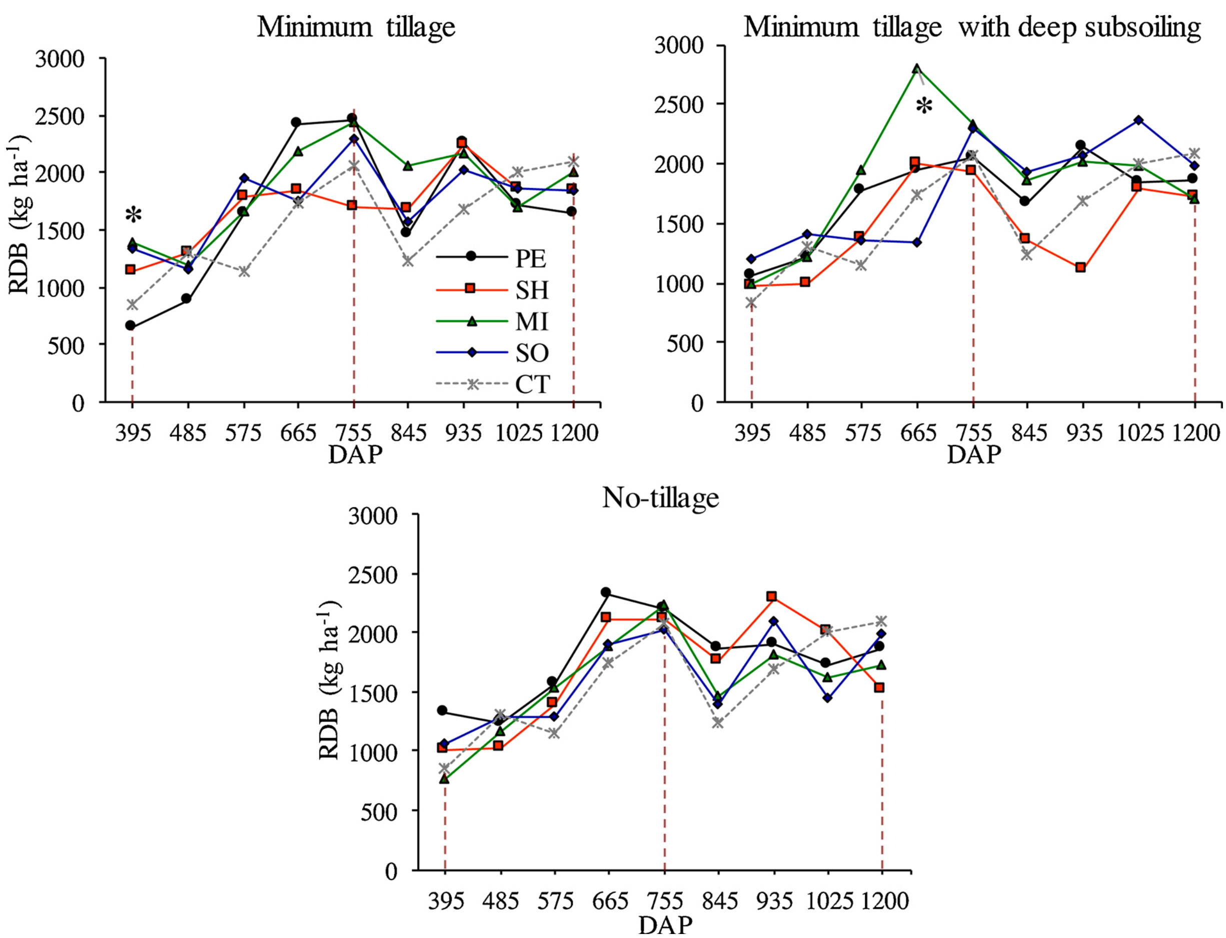

Fig. 5. Evolution of sugarcane root dry biomass (RDB) at a depth of 0.0-0.6 m over three agricultural years (cane plant, first and second ratoon cane), using different soil tillage systems and cover crops. PE = peanut; SH = sunn hemp; MI = millet; SO = sorghum; CT = conventional tillage with no cover crops; DAP = days after planting.*Significant differences by the Tukey test ($p < 0.05$) between cover crops in the same soil tillage system. Vertical dashed lines represent the time of crop harvesting.

presented the highest RDB values (466.0 and 416.2 kg ha^{-1}, respectively) in the 0.4–0.6 m layer (Table 3). An opposite behavior was observed for SO + NT and MT, with the lowest RDB values (74.9 and 145.9 kg ha^{-1}) in the same soil layer.

In the fourth sampling (665 DAP), management with SH + NT and MT/DS, PE + NT, and SO + NT showed the largest root dry biomass values in the 0.0–0.2 m layer. The lowest RDB values were obtained for SO + MT/DS, CT, SH + MT, and MI + NT. In the same soil layer and assessment time, RDB in NT was superior to the other tillage systems in association with peanut, sunn hemp, and sorghum, but in the deeper layer (0.4–0.6 m) showed an opposite behavior, presenting the lowest RDB with all cover crops. Despite having the lowest RDB values in the first layer, peanut + MT and millet + MT showed the higher biomass in the 0.2–0.4 m and 0.4–0.6 m layers, and with MT/DS millet also had the highest RDB in these layers (Table 3).

At first ratoon cane harvesting (755 DAP), in the 0.4–0.6 m layer, peanut + MT and NT showed the highest RDB among all tillage systems and cover crops. In the same layer, at 845 DAP the highest RDB was observed for MI + MT. In the eighth sampling (1025 DAP), SH + MT and NT and SO + MT/DS showed the highest RDB in the 0.0–0.2 m layer. In the last assessment, performed at 1200 DAP, no significant differences in RDB were found among the management systems; however, CT in the 0.0–0.2 m and 0.2–0.4 m layers showed the highest RDB values, 982.5 and 752.5 kg ha^{-1}, respectively (Table 3).

Over the time evaluated, the management systems of sunn hemp + NT and MT and millet + MT/DS accumulated higher sugarcane RDB in the surface layer of 0.0–0.2 m, with mean values of 905.2, 870.2 and 879.2 kg ha^{-1}, respectively, accounting for 54 %, 51 % and 47 % of the roots present in the total depth evaluated (calculated from Table 3). In the 0.2–0.4 m layer, millet + MT and MT/DS presented the highest mean RDB with 709.2 kg ha^{-1} (38 %) and 635.5 kg ha^{-1} (34 %), respectively. However, in the 0.4–0.6 m layer, the highest mean RDB values were obtained in peanut + NT and MT and millet + MT/DS with 363.4, 359.8 and 359.4 kg ha^{-1} accounting for 20.5 %, 21.4 % and 19.2 % of the number of roots in the depth of 0.0–0.6 m.

When evaluating the mean among cover crops, in the 0.0–0.20 m layer, sunn hemp obtained the highest RDB values, while peanut and CT had the lowest, but the situation is reversed when evaluating the 0.2–0.4 and 0.4–0.6 m layers, where sunn hemp and CT had the lowest means, unlike peanut and millet, which obtained the highest. This effect was also observed by evaluating the mean among soil tillage systems, where NT obtained the highest RDB values for the 0.0–0.2 m layer, but in the other layers obtained the lowest values over the cycles. Inversely, MT proved to be the tillage system with the highest means in the deeper layers. CT had means below the other tillage systems in most of the evaluated periods.

Sugarcane root density (RD) in the total soil depth (0.0–0.6 m) showed an upward trend in the first ratoon cane cycle, that is, between 395 and 755 DAP (cane plant harvesting and first ratoon cane harvesting, respectively) (Fig. 6). The highest RD values were obtained in the MT system (1.08 g dm^{-3}) at 775 DAP and in MT/DS, NT and CT systems (1.07, 1.03, and 1.03 g dm^{-3}, respectively) at 755 DAP (first ratoon cane harvesting). However, the greatest increase in RD in this period was observed in CT, from 0.41 g dm^{-3} (the lowest RD obtained at 395 DAP)

Table 3
Sugarcane root dry biomass (RDB) over three crop cycles in the 0.0-0.2 m, 0.2-0.4 m and 0.4-0.6 m layers under different soil tillage systems and cover crops.

Treatment (tillage x cover crop)		RDB (kg ha^{-1}) on different days after planting (DAP)								
		395	485	575	665	755	845	935	1025	1200
		0.0–0.2 m layer								
MT	Peanut	249.0	313.8	711.7	989.9	950.2	651.7	1032.1	710.0	740.6
	Sunn hemp	590.6	666.0	912.7	902.2	865.3	774.7	1127.8	1082.4	910.4
	Millet	627.9	532.4	674.4	960.6	1148.6	748.8	1002.6	755.8	827.1
	Sorghum	716.0	569.2	951.4	954.8	1100.3	773.2	957.5	813.8	748.8
MT/DS	Peanut	458.6	440.9	929.3	989.2	1065.8	741.1	1139.4	787.7	693.2
	Sunn hemp	540.0	522.8	801.5	1060.0	734.7	568.1	636.9	689.5	950.0
	Millet	350.6	543.0	930.7	1504.2	1093.5	781.6	1159.0	766.4	784.2
	Sorghum	710.0	571.6	596.3	699.2	1217.6	858.7	989.2	1111.5	867.1
NT	Peanut	621.9	505.0	677.9	1167.7	883.7	811.2	820.4	692.7	913.7
	Sunn hemp	511.2	540.6	860.2	1226.2	880.5	891.5	1422.1	1025.1	789.2
	Millet	349.0	518.3	747.1	949.6	923.6	712.2	1053.7	670.9	823.9
	Sorghum	410.6	677.2	672.5	1035.6	1084.4	613.9	1130.5	742.4	886.4
CT	No cover crop	368.0	520.2	466.6	842.7	1103.0	584.0	780.9	928.6	982.5
		0.2–0.4 m layer								
MT	Peanut	214.0 Bb	294.7	640.4	883.9 Aa	1004	493.9	834.2	617.8 Aa	574.4
	Sunn hemp	421.3 Aab	423.2	733.4	600.2 Abc	631.2	470.9	775.1	674.9 Aa	606.5
	Millet	432.0 Aa	443.8	731.1	771.9 Aab	923.4	812.1	878.7	662.8 Aa	727.3
	Sorghum	412.0 Aab	302.9	580.8	442.2 ABc	825.9	544.3	772.2	664.1 Ba	589.2
MT/DS	Peanut	340.0 Ba	486.5	587.5	573.4 Bab	696.9	666.6	680.2	838.4Aab	645.1
	Sunn hemp	326.6 Aa	291.1	306.0	550.1 Aab	924.7	574.3	311.6	697.4 Ab	446.6
	Millet	388.0 Aa	354.9	552.6	771.4 Aa	917.8	655.3	576.5	884.5 Aab	618.7
	Sorghum	278.0 Aa	498.2	402.0	354.7 Bb	702.0	649.1	687.6	1017.8 Aa	744.3
NT	Peanut	549.3 Aa	402.4	524.5	657.8 ABa	912.4	693.1	734.2	706.0 Aa	436.0
	Sunn hemp	276.0 Ab	248.7	466.2	652.7 Aa	852.9	568.2	605.4	699.1 Aa	427.3
	Millet	278.6 Ab	406.5	572.1	618.2 Aa	831.3	503.8	550.5	629.0 Aa	561.1
	Sorghum	462.6 Aab	461.9	377.4	672.6 Aa	762.1	404.2	682.6	430.1 Ba	629.4
CT	No cover crop	128.0	539.7	414.9	609.0	624.1	341.8	613.4	892.6	752.5
		0.4–0.6 m layer								
MT	Peanut	181.3 Aa	274.1	298.2 Aab	543.8 Aa	513.4 Aa	324.4 Aab	389.8	386.1 Aa	327.3
	Sunn hemp	120.0 Aa	218.1	145.9 Ab	344.2 Aab	206.3 Ab	429.9 Aab	349.1	111.8 Bb	321.8
	Millet	338.6 Aa	226.8	257.2 ABab	459.5 Aab	365.3 Aab	494.8 Aa	282.9	279.7 Aab	455.8
	Sorghum	206.0 Aa	277.5	416.6 Aa	265.5 Ab	368.2 Aab	261.4 Ab	301.1	385.2 Aa	516.5
MT/DS	Peanut	257.3 Aa	298.4	258.9 Aa	390.7 Aa	295.6 Aa	269.8 Aa	326.4	216.1 Aa	529.4
	Sunn hemp	106.0 Aa	178.5	265.0 Aa	393.0 Aa	265.0 Aa	206.5 Ba	162.6	404.1 Aa	328.0
	Millet	245.3 ABa	320.4	466.0 Aa	516.6 Aa	320.7 Aa	431.3 ABa	285.1	340.7 Aa	308.1
	Sorghum	208.0 Aa	331.3	355.2 Aa	282.6 Aa	370.5 Aa	415.8 Aa	398.4	240.8 Aa	373.5
NT	Peanut	146.0 Aa	320.8	360.1 Aa	487.4 Aa	408.4 Aa	369.8 Aa	338.1	319.1 Aa	520.6
	Sunn hemp	216.0 Aa	235.6	74.9 Ab	239.2 Aab	379.3 Aab	304.1 ABa	257.4	283.0 ABa	290.7
	Millet	126.0 Ba	237.8	212.5 Bab	314.9 Aab	476.0 Aa	243.1 Ba	215.8	329.1 Aa	335.6
	Sorghum	194.6 Aa	150.8	231.5 Aab	184.5 Ab	173.2 Ab	380.8 Aa	287.8	275.4 Aa	465.5
CT	No cover crop	148.0	243.5	261.3	293.5	341.8	238.2	294.2	183.5	356.2

Lower case letters compare cover crops for the same tillage system and uppercase letters compare tillage systems for the same cover plant. Means followed by the same letter do not differ statistically from each other by Tukey's test ($p < 0.05$). Numbers in *italics* represent the percentage of RDB in each layer in relation to the total in the depth of 0.0–0.6 m.

to 1.03 g dm^{-3}, an increase of 0.62 g dm^{-3}, equivalent to 151 %.

In the second ratoon cane cycle (755–1200 DAP), RD showed a reduction at 845 DAP in all tillage systems, dropping to 0.82, 0.81, 0.80 and 0.62 g dm^{-3} in MT/DS, MT, NT and CT, respectively, a reduction of 23 %, 25 %, 22 % and 40 % (Fig. 6). The highest RD was obtained at 935 DAP in NT, MT, and MT/DS. However, in CT it obtained at 1200 DAP (second ratoon cane harvesting), is also the largest RD among all soil tillage systems.

RD was concentrated in the surface layer (0.0–0.2 m), reducing with increasing depth and showing mean values between 1.38 g dm^{-3} in peanut + MT and 1.79 g dm^{-3} in sunn hemp + NT (Fig. 6). CT showed low RD in this soil layer, with a value of 1.42 g dm^{-3}, the same obtained in sunn hemp + MT/DS, not increasing with depth and maintaining the low RD behavior in the two remaining soil layers, resulting in a total-depth in mean RD of 0.77 and 0.74 dm^{-3} for these management systems.

In all soil tillage systems, root volume (RV, Fig. 7A), root surface area (RA, Fig. 7B) and total root length (TRL, Fig. 8) showed the lowest values at cane plant harvesting (394 DAP), first ratoon cane harvesting (845 DAP) and second ratoon cane harvesting (1200 DAP), but, no significant differences were found between treatments. In the first ratoon cane cycle, the behavior of those attributes followed the behavior obtained for RD (Fig. 6), with an increase in RV, RA, and TRL as RD increased over time. However, in the second ratoon cane cycle, the highest RV, RA, and TRL values were obtained at 935 DAP, followed by a reduction of these attributes up to second ratoon cane harvesting (1200 DAP). The behavior of the root system attributes over time for CT is noteworthy: contrary to what was observed for RD, there was a reduction in RV, RA, and TRL as RD increased. It is noteworthy that for none of the evaluated attributes there were significant differences in the assessments.

Regarding root length in diameter classes ($RL_{0.5}$, $RL_{0.5-2.0}$, and $RL_{2.0}$), a predominance of thin (dr <0.5 mm) and medium (0.5 mm $\leq$ dr $\leq$ 2.0 mm) roots was observed in all tillage systems (Fig. 8). During the entire assessment period, MT showed between 47 % and 52 % of the length corresponding to thin roots, between 43 % and 48 % to medium roots, and between 3 % and 6 % too thick roots.

The MT/DS system showed root length between 48 % and 53 % corresponding to fine roots, between 43 % and 47 % to medium roots, and between 3 % and 6 % too thick roots. The NT system showed between 48 % and 52 % of total length in the thin roots class, between 44 % and 46 % in the medium roots class, and between 4 % and 6 % in the thick roots class. CT showed a total length between 48 % and 53 % corresponding to fine roots, between 43 % and 50 % to medium roots, and between 3 % and 7 % too thick roots (Fig. 8).

Tillage	Cover crop	Depth (m)	Root density (g dm^{-3}) at different DAP									
			395	485	575	665	755	845	935	1025	1200	Mean
MT	Peanut	0.0-0.2	0.49	0.63	1.43	1.92	1.89	1.22	2.00	1.40	1.48	1.38
		0.2-0.4	0.23	0.31	0.67	0.93	1.06	0.52	0.88	0.65	0.60	0.65
		0.4-0.6	0.19	0.29	0.31	0.57	0.54	0.34	0.41	0.41	0.34	0.38
	Sunn hemp	0.0-0.2	1.18	1.31	1.83	1.78	1.68	1.56	2.03	2.18	1.83	1.71
		0.2-0.4	0.44	0.45	0.77	0.63	0.66	0.50	0.82	0.71	0.64	0.62
		0.4-0.6	0.13	0.23	0.15	0.36	0.22	0.45	0.37	0.12	0.34	0.26
	Millet	0.0-0.2	1.24	1.02	1.34	1.88	2.18	1.48	2.01	1.48	1.63	1.58
		0.2-0.4	0.45	0.47	0.77	0.81	0.97	0.85	0.93	0.70	0.77	0.75
		0.4-0.6	0.36	0.24	0.27	0.48	0.38	0.52	0.30	0.29	0.48	0.37
	Sorghum	0.0-0.2	1.34	1.12	1.82	2.08	2.19	1.48	1.78	1.58	1.51	1.66
		0.2-0.4	0.43	0.32	0.61	0.47	0.87	0.57	0.81	0.70	0.62	0.60
		0.4-0.6	0.22	0.29	0.44	0.28	0.39	0.28	0.32	0.41	0.54	0.35
	Mean	0.0-0.6	0.56	0.56	0.87	1.02	1.08	0.81	1.05	0.88	0.90	0.86
MT/DS	Peanut	0.0-0.2	0.91	0.84	1.85	1.95	2.09	1.47	2.19	1.57	1.34	1.58
		0.2-0.4	0.36	0.51	0.62	0.60	0.73	0.70	0.72	0.88	0.68	0.64
		0.4-0.6	0.27	0.31	0.27	0.41	0.31	0.28	0.34	0.23	0.56	0.33
	Sunn hemp	0.0-0.2	1.05	1.04	1.60	2.07	1.47	1.09	1.25	1.34	1.86	1.42
		0.2-0.4	0.34	0.31	0.32	0.58	0.97	0.60	0.33	0.73	0.47	0.52
		0.4-0.6	0.11	0.19	0.28	0.41	0.28	0.22	0.17	0.43	0.35	0.27
	Millet	0.0-0.2	0.68	1.06	1.82	3.00	2.19	1.56	2.29	1.50	1.53	1.74
		0.2-0.4	0.41	0.37	0.58	0.81	0.97	0.69	0.61	0.93	0.65	0.67
		0.4-0.6	0.26	0.34	0.49	0.54	0.34	0.45	0.30	0.36	0.32	0.38
	Sorghum	0.0-0.2	1.31	1.08	1.13	1.38	2.38	1.67	1.95	2.18	1.69	1.64
		0.2-0.4	0.29	0.52	0.42	0.37	0.74	0.68	0.72	1.07	0.78	0.62
		0.4-0.6	0.22	0.35	0.37	0.30	0.39	0.44	0.42	0.25	0.39	0.35
	Mean	0.0-0.6	0.52	0.58	0.81	1.03	1.07	0.82	0.94	0.96	0.88	0.85
NT	Peanut	0.0-0.2	1.25	0.97	1.31	2.29	1.74	1.61	1.63	1.39	1.80	1.55
		0.2-0.4	0.58	0.42	0.55	0.69	0.96	0.73	0.77	0.74	0.46	0.66
		0.4-0.6	0.15	0.34	0.38	0.51	0.43	0.39	0.36	0.34	0.55	0.38
	Sunn hemp	0.0-0.2	1.02	1.05	1.74	2.43	1.69	1.77	2.78	2.06	1.60	1.79
		0.2-0.4	0.29	0.26	0.49	0.69	0.90	0.60	0.64	0.74	0.45	0.56
		0.4-0.6	0.23	0.25	0.08	0.25	0.40	0.32	0.27	0.30	0.31	0.27
	Millet	0.0-0.2	0.68	1.01	1.51	1.86	1.84	1.38	2.13	1.34	1.63	1.49
		0.2-0.4	0.29	0.43	0.60	0.65	0.88	0.53	0.58	0.66	0.59	0.58
		0.4-0.6	0.13	0.25	0.22	0.33	0.50	0.26	0.23	0.35	0.35	0.29
	Sorghum	0.0-0.2	0.81	1.30	1.33	2.06	2.09	1.20	2.15	1.41	1.73	1.56
		0.2-0.4	0.49	0.49	0.40	0.71	0.80	0.43	0.72	0.45	0.66	0.57
		0.2-0.4	0.20	0.16	0.24	0.19	0.18	0.40	0.30	0.29	0.49	0.27
	Mean	0.0-0.6	0.51	0.58	0.74	1.05	1.03	0.80	1.05	0.84	0.88	0.83
CT	No cover crop	0.0-0.2	0.71	1.02	0.94	1.67	2.06	1.16	1.46	1.82	1.96	1.42
		0.2-0.4	0.35	0.57	0.44	0.64	0.66	0.44	0.65	0.94	0.79	0.61
		0.4-0.6	0.16	0.26	0.28	0.31	0.36	0.25	0.31	0.19	0.37	0.28
	Mean	0.0-0.6	0.41	0.62	0.55	0.87	1.03	0.62	0.81	0.98	1.04	0.77

Fig. 6. Distribution of sugarcane root density (g dm^{-3}) in the layers of 0.0-0.2 m, 0.2-0.4 m, and 0.4-0.6 m over three crop cycles and under different soil tillage systems and cover crops. MT = minimum tillage; MT/DS = minimum tillage with deep subsoiling; NT = no-tillage; CT = conventional tillage; DAP = days after planting. Darkening green shades indicate an increase in RDB percentage.

4. Discussion

4.1. Root dry biomass (RDB) and root density (RD)

The behavior of the sugarcane root system over time was hardly influenced by cover crops since significant differences in RDB were only found at 395 DAP in MT and 665 DAP in MT/DS. Those periods relate to the cane plant cycle and the first ratoon cane cycle, respectively. This indicates that the effects of cover crops on the sugarcane root system may not last over time, adding that as the crop cycles progress, sugarcane harvesting operations generate heavy machinery traffic, significantly increasing soil compaction. Alameda et al. (2012) found that plant responses to soil compaction are firstly manifested in changes in root characteristics and functioning, resulting in a reduction in root length and the number of thin roots.

In general, sugarcane showed the lowest root dry biomass and root density at the time of cane plant harvesting (395 DAP) and ninety days after that harvesting (485 DAP), presenting in that period the least variation of such attributes over time. Subsequently, RDB increased progressively until reaching the maximum value at first ratoon cane harvesting (755 DAP), followed by a significant drop over ninety days after such harvesting (845 DAP), leading also to a reduction in root density, volume, surface area and length. Faroni and Trivelin (2006) point out that after sugarcane is cut, the roots preserve their activity for a while and are later replaced by ratoon roots, resulting in an accumulation of root biomass, as verified in this study at the two crop harvests

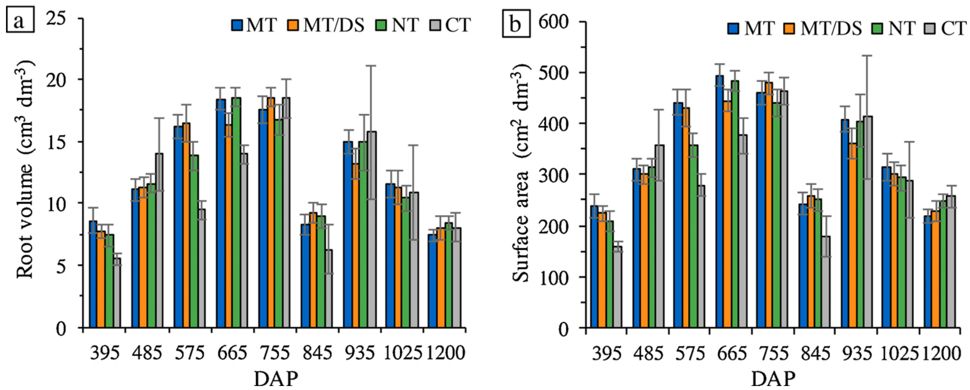

Fig. 7. Sugarcane root volume at a depth of 0.0-0.6 m under different soil tillage systems. MT = minimum tillage; MT/DS = minimum tillage with deep subsoiling; NT = no-tillage; CT = conventional tillage; DAP = days after planting. Error bars represent standard error.

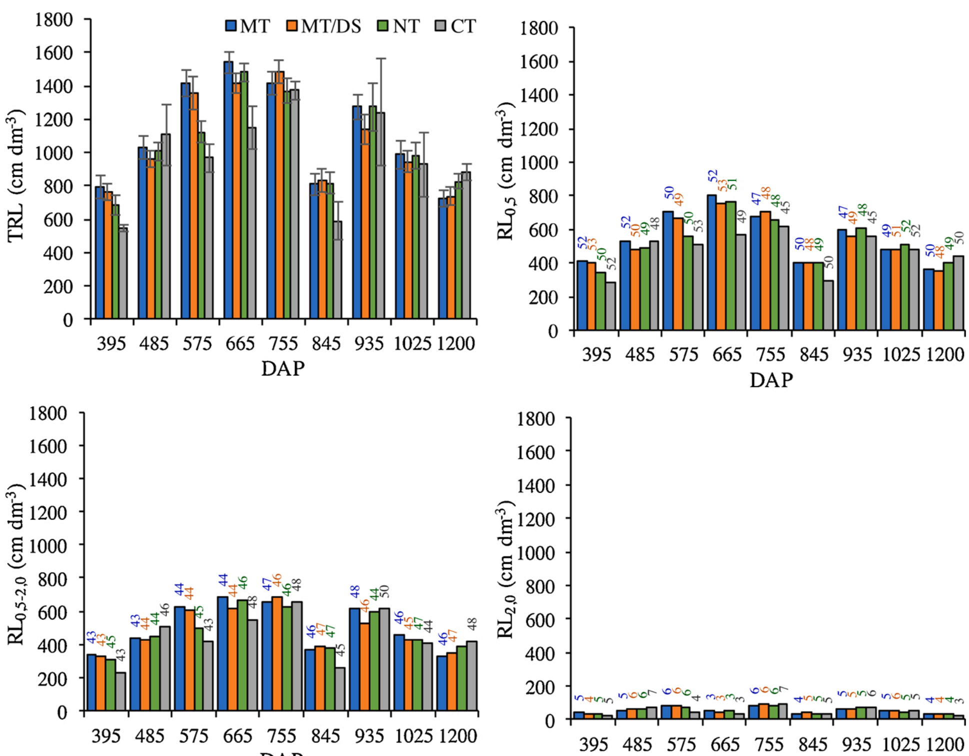

Fig. 8. Total sugarcane root length (TRL) at a depth of 0.0–0.6 m under different soil tillage systems and root length in the following diameter (dr) classes: dr <0.5 mm ($RL_{0.5}$), 0.5 mm ≤ dr ≤ 2.0 mm ($RL_{0.5\text{-}2.0}$) and dr> 2.0 mm ($RL_{2.0}$). MT = minimum tillage; MT/DS = minimum tillage with deep subsoiling; NT = no-tillage; CT = conventional tillage; DAP = days after planting. Error bars represent standard error. Numbers above the column show the percentage of the length of each class in relation to total length.

(395 and 755 DAP).

According to Vasconcelos and Dinardo-Miranda (2011), the process of death or renewal of the sugarcane root system depends on soil drying and moistening cycles rather than on the cutting of the plant's aerial part. One notes that rainfall, resulting in changes in the hydric balance (Fig. 4), decreased over the cycles and RDB (Fig. 5) responded with a reduction in root growth between the first and second ratoon cane cycles. Between 575 and 755 DAP, there was an increase in RDB, while this behavior did not occur during the second ratoon cane cycle, in which the amount of RDB was close to linear. This confirms that the root system depends on the amount of rainfall and hydric balance in the area, corroborating the findings of Mazurana et al., (2013) who inferred that the greater availability of water in the soil led to greater root growth due to lower soil resistance to penetration, acting as a lubricating effect between root-soil and a decrease in cohesion forces that hold particles together in the soil structure.

Among the soil tillage systems evaluated (Fig. 5), NT showed the least differences among cover crops, with a behavior that was closer to CT. In turn, in the conservation systems with more soil revolving, mainly MT and MT/DS, there were greater differences among treatments. This might result from the "age hardening effect" (Moraes et al., 2017), which is the process in which the soil strength increases with time andrelated to the formation of new inter-particle bonds or to the strengthening of an existing one, where, despite NT generating greater RP values, seemingly causing greater difficulty to root system development, in reality, due to its less altered structure. It results in more developed root systems when compared to conventional tillage in the long run, or the same amount if considered a shorter period, as in this study.

However, in addition to the assessment between cycles, it is important to know the amounts of root in the evaluated layers, not just the total sum, as obtained in Fig. 5. Therefore, the authors evaluated the differences by treatments and layers, in a more detailed view of the effects of tillage systems and cover crops.

It is noteworthy that significant differences occurred only in the 0.2−0.4 m and 0.4−0.6 m layers, that is, the deeper ones. This shows that in the sandy layer of the soil (Table 1), where root growth penetrates more easily, there were no impediments to growth, and all treatments achieved similar growth. In turn, in the more clayey layer (0.3−0.6 m), due to greater depth and textural change, in treatments that generate more sensitive root systems, there is greater difficulty to penetrate, and thus greater differences in the root system occur.

Also, the greatest amount of significant differences occurred in the 0.4−0.6 m layer, that is, the treatments that favored expressive root growth in this layer possibly stood out in relation to the others, leading to the conclusion that the 0.4−0.6 m layer is the main factor behind differences between treatments. Added to this, it is observed that in both layers the differences occur at 665 and 1025 DAP, which are the samplings before the first and second ratoon cane harvest, respectively. In other words, at the moment of the cycle when there is greater root growth, enables the observation of treatments that obtained the greatest development. The treatments using peanut + MT and NT and millet + MT and MT/DS stand out in both layers as the largest production in dry biomass in the sampling at 665 DAP, while peanut, millet, and sorghum + MT/DS stand out for the sampling at 1025 DAP.

In the long term, there are already studies proving the benefits of NT such as preserving straw in the soil (Castioni et al., 2019), reducing the contact pressure of tires (Vischi Filho et al., 2015), and increasing soil macrofauna (Castioni et al., 2018). However, since NT did not obtain favorable results, especially at the beginning of the cycle, as afterward there is a trend towards equalization among treatments, corroborated by Barbosa et al. (2018), who evaluated the root system in the long term as in this study. It is suggested that producers start the transition from conventional tillage to no-tillage using MT or MT/DS, as these systems have short-term benefits for producers when compared to NT and facilitate the transition to NT in the future.

Studying the characteristics of the sugarcane root system under different tillage systems, after first harvesting (1.5 years), Moraes et al. (2019) found that root length density at the depth of 0.0−0.9 m was higher in treatments that included plowing operations than in conservation managements, with 0.329 $cm^3\ cm^{-3}$ in management consisting of weed desiccation and moldboard plowing (0.4 m) and light harrowing (0.15 m), 0.287 $cm^3\ cm^{-3}$ in management of weed desiccation and subsoil plowing (0.4 m) and 0.276 $cm^3\ cm^{-3}$ in management of weed desiccation and no-tillage. These results are also reflected in higher sugarcane yield with management practices with greater soil revolving (plowing and harrowing).

Conventional tillage without the use of cover crops causes greater soil revolving in the surface layer, and also resulted in less machinery traffic on the soil due to the smaller number of tire passages in the interrow centers (Fig. 2). Conversely, minimum tillage and minimum tillage with deep subsoiling combined with the peanut cover crop had the most intense traffic during the implementation of the experiment, a fact that may have influenced the lower RDB content in the peanut + MT management system in the first sampling carried out at 395 DAP and the low root concentrations in the first two soil layers, resulting from compaction caused by machinery traffic. Soil compaction is considered by authors such as Bengough et al. (2011) and Otto et al. (2011) as the main limiting factor in root growth.

The low sugarcane RDB values in the peanut + MT management system may also be explained by the peanut harvesting process, which involves great soil disturbance, requiring mechanized pull-out of the plants during harvesting. This involves the use of a device called digger-shaker which digs into the soil at a depth of approximately 0.05 m below the pods, uprooting the plants and organizing the pods on the soil surface for sun drying. A subsequent harvesting stage consists of collecting and separating the plants with a device called pick-beater, which separates the pods from the plant (Santos et al., 2009). This sequence of events favors soil structure degradation, causing soil compaction.

Through root distribution, it was found that the highest root concentration occurs in the surface layers of the soil, regardless of the management system used. In general, sugarcane root biomass was more concentrated in the surface layer of 0.0−0.2 m over time, with values between 35 % and 62 % of RDB. In the first crop cycle, at 395 DAP, RDB concentration with depth was 48 %, 33 %, and 19 % for the 0.0−0.2 m, 0.2−0.4 m and 0.4−0.6 m layers, respectively, results similar to those obtained by Otto et al. (2009), who reported sugarcane RDB concentrations of 52 %, 28 % and 20 % in the same soil layers and using the same assessment methodology used in this study. Other studies corroborate the higher concentration of the root system in surface layers (Alvarez et al., 2000; Cury et al., 2014; Aquino et al., 2015; Barbosa et al., 2018; Rossi Neto et al., 2018; Esteban et al., 2019).

Distribution of the root system with depth and its interaction with the environment has a direct impact on some factors such as drought tolerance, germination and/or sprouting capacity, plant size, tolerance to machinery traffic, efficiency in absorbing soil nutrients, among others (Vasconcelos and Dinardo-Miranda, 2011). Different authors, such as Medina et al. (2002) and Bengough et al. (2011), highlight that the greater the plant's rooting, the greater its capacity to exploit the soil and take advantage of nutrients, water, and oxygen.

Another factor that facilitates the concentration of the root system in surface layers is the use of green manure, which is related to the C/N ratio, in the case of legumes, and also to biological nitrogen fixation and its relationship with the mycorrhizae existing in the soil, benefiting the root system (Ambrosano et al., 2011). The opposite also occurs in cover crops with less-developed root systems that have more difficulty to absorb water and nutrients, as the roots do not reach deep enough to better withstand drought periods, as in the case of peanut, which obtained lower values compared to the other cover crops, possibly reducing sugarcane yield in soil tillage systems that used this cover crop.

Therefore, greater root concentration in the surface layers of the soil is noted, especially the 0.0−0.2 m layer, as expected due to soil texture and crop behavior. It is noteworthy that the layer which most benefited from soil tillage or cover crops was 0.4−0.6 m, since, being the most clayey layer, it was the most difficult to penetrate and, consequently, the most challenging for the root system. This study found that the use of the MT and MT/DS systems showed a greater capacity for penetration in those layers, mainly associated with millet and sunn hemp.

4.2. Root length, volume and area

In all management systems and assessed periods, was found the prevalence of thin ($dr<0.5$ mm) and medium ($0.5 < dr < 2.0$ mm) roots, a relevant fact for the proper physiological functioning of the crop, since roots with diameters below 2.0 mm are important for the absorption (thin roots) and transport (medium roots) of water and nutrients (Chimento and Amaducci, 2015). Also, Morris and Tai (2004) indicate a positive correlation of sugarcane yield with dry biomass and root length, and with high length values for thin and medium roots and low values for thick roots.

Analyzing the root system and yield of sugarcane ratoons under different amounts of straw, Aquino et al. (2015) found that the surface layer is vulnerable to weather conditions, with direct influence on the root system, causing a decrease in the crop's yield and root system in unfavorable environmental situations. This fact may also have influenced the occurrence of low RDB values in the conventional tillage system and, therefore, of low root density, volume and surface area, and root length at cane plant harvesting (395 DAP), as in the first crop cycle the absence of cover crops in this treatment exposes the soil surface to greater loss of soil moisture.

It should be noted that root density (RD) in conservation management systems differed from conventional tillage in seven of the nine assessments carried out over time. Up to 935 DAP, RD was greater in minimum tillage, minimum tillage with deep subsoiling and no-tillage; however, at 1025 and 1200 DAP, conventional tillage presented greater RD. Nevertheless, some authors point out that high energy expenditure for the maintenance of the root system may have negative consequences for the crop, such as reduced yield (Otto et al., 2009;

Barbosa et al., 2018). Therefore, the study of root development must be associated with crop yield to better understand the benefits of the development of the root system throughout the sugarcane cycles.

One of the advantages of assessment during the sugarcane cycle is the possibility of finding the behavior over the cycle, which may not be constant, as shown in Fig. 7. In this study, one notes that during the first ratoon cane cycle (16/17) there was a constant increase in root volume and surface area, while for the second ratoon cane cycle (17/18), there was a reduction after harvesting (845 DAP) followed by an increase (935 DAP), as in the previous cycle, but followed by a constant reduction after 935 DAP. This behavior is due to the increase in rainfall (Fig. 4) that occurred during the third cycle, especially between November and March, much higher than in the previous cycle. Therefore, due to the water surplus, the crop did not feel the need to expend energy with deep root growth.

This effect is known as "luxury consumption" (Muchow et al., 1996) because the plant has more water than it needs. Consequently, after their initial development, in the case of this study, the roots not only stopped growing but also started to decompose more quickly due to the excess of water accumulated in the surface layer (Table 1), causing a reduction in root volume and surface area (Fig. 4).

Therefore, one of the distinctive aspects of this study was the possibility of perceiving these small details that go undetected in situations of more spaced out samplings. Also, it is noteworthy that as rainfall is homogenous in the area, there were no differences among the treatments due to the amount of water received.

4.3. Effects of soil tillage systems and cover crops on the root system and yield

From the data presented, it was possible to notice that the treatments had significant effects at the depths of 0.2−0.6 m, where differences were found, especially in the deepest layer (0.4−0.6 m). Also, the greatest differences occurred before sugarcane harvesting (665 and 1025 DAP) for both layers (0.2−0.4 m and 0.4−0.6 m).

However, despite the differences in root attributes, the same did not occur for yield (Table 2), as there were no statistical differences in any of the evaluated cycles. This effect was expected because, following the first ratoon cane cycle, the effects of tillage systems and cover crops are minimized, thereby reducing the differences. This effect was also found by Barbosa et al. (2018), who evaluated conventional tillage and no-tillage in different soil textures and found that this is common regardless of the texture evaluated.

These results agree with those of Oliveira et al. (2019) who, at the same study site, found no differences in water content and soil physical attributes among treatments during the first ratoon cane cycle. In other words, the effects of soil tillage and cover crops are less pronounced in the cane plant cycle, that is, closest to the moment of soil tillage and before harvester and wagon traffic, when there is a greater risk of soil compaction (Guimarães Júnnyor et al., 2019).

As a result, the authors suggest that further studies should be carried out evaluating the root system at various times of the year, allowing a more in-depth evaluation of the effects of the weather and management systems. That way they will be able to improve the root system, physical soil attributes and yield without compromising their yield and profit, thus ensuring environmental sustainability, which is a common goal, without renouncing financial sustainability, which is the main focus of producers.

5. Conclusions

The tillage systems and cover crops influenced the root development of sugarcane

The highest concentration of root dry biomass was obtained in the 0.0−0.2 m surface layer, containing between 36 % and 62 % of roots present in the first 0, 6 m deep. However, the significant differences between the soil tillage and cover crops occur in the clayey layer of the soil (0.30−0.6 m), where the management effects affected the root system.

Few differences in sugarcane root development were obtained among cover crops within each tillage system. Differences in the dry biomass of the roots were obtained in the minimum and minimum tillage with deep subsoiling, only at the time of harvesting the first crop cycle (cane plant, 395 days after planting) and in the second cycle, 665 days after planting, respectively.

The highest sugarcane root density was obtained at 655 days after planting in no-tillage and 755 days after planting in minimum tillage, minimum tillage with deep subsoiling, and conventional tillage, indicating that the highest concentration of roots occurs at the time of first ratoon cane harvesting.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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