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Sugarcane Root Development and Yield under Different Soil Tillage Practices

Emmerson Rodrigues de Moraes[(1)], José Geraldo Mageste[(2)], Regina Maria Quintão Lana[(2)], José Luiz Rodrigues Torres[(3)], Luis Augusto da Silva Domingues[(4)], Ernane Miranda Lemes[(2)] and Luara Cristina de Lima[(5)*]

(1) Instituto Federal de Educação, Ciência e Tecnologia Goiano, *Campus* Morrinhos, Departamento de Agronomia, Morrinhos, Goiás, Brasil.
(2) Universidade Federal de Uberlândia, Instituto de Ciências Agrárias, *Campus* Umuarama, Uberlândia, Minas Gerais, Brasil.
(3) Instituto Federal de Educação, Ciência e Tecnologia, *Campus* Uberaba, Departamento de Agronomia, Uberaba, Minas Gerais, Brasil.
(4) Instituto Federal de Ciência e Tecnologia do Triângulo Mineiro, *Campus* Uberlândia, Uberlândia, Minas Gerais, Brasil.
(5) Universidade Federal de Uberlândia, Instituto de Ciências Agrárias, *Campus* Uberlândia, Programa de Pós-Graduação em Agronomia, Uberlândia, Minas Gerais, Brasil.

*** Corresponding author:**
E-mail: lima_luara@yahoo.com.br

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ABSTRACT: New strategies for sugarcane production have been very important since the incorporation of ethanol in the Brazilian energy mix in the early 1970s. Prior to planting sugarcane, the soil is prepared, and this process can affect root development and, consequently, sugarcane production. This study was conducted in an area of sugarcane crop renewal in the Cerrado biome (Brazilian tropical savanna), with the objective of identifying which tillage system generates the better root development and improved yield in sugarcane. The treatments were: 1) weed desiccation + moldboard plowing (0.4 m) + mild spike tooth harrowing (0.15 m); 2) subsoiler (0.3 m) + mild spike tooth harrowing (0.15 m); 3) weed desiccation + no-tillage (furrow opening and fertilizer); 4) weed desiccation + subsoiler (0.4 m); 5) ratoon destruction + subsoiler (0.4 m); 6) ratoon destruction + spike tooth harrowing (0.2 m) + moldboard plowing (0.4 m) + mild spike tooth harrowing (0.15 m). Characteristics of the sugarcane root system, such as the root length density, average distance between roots, and root soil exploration, after the first harvest (1.5 years) were studied. Root length density was greater for the treatments that included plowing (0.4 m) and harrowing (0.15 m) operations. The average distance between roots was low in the no-tillage system. The highest sugarcane yield in the plant crop was achieved by management practices with more extensive soil profile disturbances, like plowing followed by harrowing.

Keywords: no-till farming, root system development, *Saccharum officinarum*, soil tillage systems.

INTRODUCTION

The soil environment for crop production is highly determined by factors such as climate and management of the topsoil layer. Soil properties are greatly affected by tillage operations, which can change water and nutrient availability, the total soil volume explored by roots, and the soil physical properties (Baquero et al., 2012).

The use of heavy machineries and implements has allowed tillage of extensive areas with considerable turnover of top soil, which is intended to maximize the conditions for root development in the short term (Arruda et al., 2016). However, some of these practices performed indiscriminately may be harmful to soil by reducing aeration and water movement, resulting in significant differences in plant growth and production.

The main functions of the sugarcane root system are soil solution uptake, transport and storage of water and nutrients, and plant structural support. The efficiency of those functions depends on several physiological mechanisms and has a direct effect on sugarcane plant stature, tolerance to machinery traffic, tillering capacity, drought resistance, efficient water and plant nutrition, pest and disease tolerance, and plant production (Otto et al., 2011).

Many biological, chemical, and physical soil properties can influence root architecture. Interventions with tillage operations and additional fertilization aim to correct possible deficiencies in these soil properties. It has been shown that areas of sugarcane crop renewal benefit from continuous cultivation and repetitive practices of the same crop regarding soil water storage capacity, soil cation exchange capacity, and chemical interactions between the top soil layer and the subsurface (Prado and Pancelli, 2008). However, knowledge regarding the adequacy of the soil physical environment in areas of sugarcane crop renewal - which have been under successive years of the same cropping practices- is lacking.

Thus, the aim of this study was to identify the soil preparation system for areas of sugarcane crop renewal that provide greater yield and a better environment for the development of sugarcane roots in the first harvest.

MATERIALS AND METHODS

The experiment was conducted in the Brazilian Cerrado (savanna-like biome) in the municipality of Goianésia, state of Goiás, Brazil (15° 10' S, 49° 15’ W, 640 m a.s.l.) in an area where sugar cane stalk shave been harvested for 8 years. The soil is classified as a *Latossolo Vermelho distrófico* (Santos et al., 2013), which corresponds to an Oxisol Udic (Soil Survey Staff, 2014). Soil chemical properties at the beginning of the study are shown in tables 1 and 2.

Table 1. Soil chemical characterization at the 0.00 to 0.20 and 0.20 to 0.40 m soil layers

pH(H_2O)	Ca^{2+}	Mg^{2+}	Al^{3+}	P	K	H+Al	T	V	m	OM
	——— $cmol_c$ dm^{-3} ———			—— mg dm^{-3} ——		—— $cmol_c$ dm^{-3} ——		——— % ———		g kg^{-1}
					0.00 to 0.20 m					
5.15	1.73	0.66	0.02	1.30	54.00	2.54	5.07	49.7	1.38	19.3
					0.20 to 0.40 m					
4.63	0.45	0.32	0.37	0.95	6.83	3.02	3.80	20.1	33.00	13.9

pH in H_2O at a ratio of 1:2.5 v/v. Ca^{2+}, Mg^{2+}, and Al^{3+} extracted with KCl solution (1 mol L^{-1}); P and K extracted with HCl 0.05 mol L^{-1} + H_2SO_4 0.0125 mol L^{-1}; available P extracted with Mehlich-1; H+Al = SMP buffer solution - pH 7.5; T = CEC at pH 7.0; V = base saturation; m = Al^{3+} saturation; OM = organic matter determined by the colorimetric method (Donagema et al., 2011).

Table 2. Soil physical characterization from the 0 to 0.9 m soil layer

Layer	CS	FS	Silt	Clay	Texture[1]
m		g kg^{-1}			
0.00-0.20	143	330	96	431	Clayey
0.20-0.40	115	338	98	450	Clayey
0.40-0.60	116	319	105	461	Clayey
0.60-0.90	107	313	104	477	Clayey

[1] Pipette method (Donagema et al., 2011). CS = coarse sand (0.5-1 mm); FS = fine sand (0.05-0.2 mm).

The predominant climate of the region is Aw (megathermal type), according to the Köppen classification system, which is a hot climate with rainy summers and dry winters. The average temperature variations during the experimental period were 21.8 °C in June and 26.1 °C in January. Rain accumulation was 1,435 mm during the first year of cultivation and 570 mm in half of the following year, when the evaluations and first cut of sugarcane occurred.

A randomized block design (RBD) with four replications in a 6 × 4 factorial arrangement, consisting of six tillage treatments and four soil layers (0.00-0.20, 0.20-0.40, 0.40-0.60, 0.60-0.90 m) was used to compare the presence of roots in the soil. To study the variation of root attributes in accordance with the horizontal distance between the plant rows, a randomized block design in 6 × 5 factorial arrangement was used, consisting of six tillage treatments and five distances from the ratoon (in the plant rows and 0.45 and 0.75 m to the right and to the left).

The six tillage treatments are combinations of different implements and tillage operations for the purpose of incorporating lime, eliminating compacted layers, and incorporating weeds prior to sugarcane planting. Each plot was 50 m long and 19.5 m wide and composed of 13 rows of sugarcane at a spacing of 1.5 m between rows. The blocks and the plots were separated by 5-m wide field access lanes to facilitate machinery and implement maneuvers.

The tillage treatments were: 1) weed desiccation + moldboard plowing (0.4 m) + mild spike tooth harrowing (0.15 m) - (WPH); 2) subsoiler (0.3 m) + mild spike tooth harrowing (0.15 m) - (SH); 3) weed desiccation + no-tillage (furrow opening and fertilizer) - (WNT); 4) weed desiccation + subsoiler (0.4 m) - (WS); 5) ratoon destruction + subsoiler (0.4 m) - (RDS); 6) ratoon destruction + spike tooth harrowing (0.2 m) + moldboard plowing (0.4 m) + mild spike tooth harrowing (0.15 m) - (RHPH).

"Ratoon destruction" consisted of uprooting the sugarcane ratoons by using a sub soiler in the sugarcane rows. For weed desiccation, the herbicides glyphosate (at the rate of 2 L ha^{-1}) and 2.4-D (at the rate of 2 L ha^{-1}) were used. Prior to setting up the treatments, dolomitic limestone (1.5 t ha^{-1} in a single application, RER 85 %) was applied, followed by gypsum application in the entire area (0.8 t ha^{-1}).

All treatments were set up and planted manually by placing 15-20 buds per meter of furrow; the variety used was IAC 87-3396 (Afcrc, 2009). The furrows were opened mechanically, with a furrow opener plus fertilizer application of 250 kg ha^{-1} of monoammonium phosphate. Five months after planting, at the beginning of the rainy season (September), a formulated liquid fertilizer 5-0-13 (NPK) + 0.3 % Zn + 0.3 % B (1,000 L ha^{-1}), equivalent to 50 kg ha^{-1} of N, 130 kg ha^{-1} of K_2O, and 3 kg ha^{-1} of Zn and B, was applied in top dressing.

Root development was evaluated at 1.5 years after planting using the methodology of evaluation *in situ*, with counting of root intersection in the soil profile by the "profile wall method" (Azevedo et al., 2011). To make this count, a 1.5 m width by 0.8 m depth was opened in each plot. The soil profile wall was cut at a 90° angle in relation to the bottom of the pit.

The roots were exposed in the entire soil profile using a rake. A 1.5 m wide by 0.8 m deep screen was fixed on the soil profile. Fifteen squares on the horizontal and eight squares on the vertical dimension (0.1 × 0.1 m meshes) composed the profile of each evaluation unit, and the number of roots in each section and intersection was counted.

To estimate stalk weight per hectare, the area was burned and the stalks of the five center rows of each plot were cut manually (evaluated area: 375 m^2). Stalk weigh was assessed with the aid of a dynamometer coupled to a tractor.

Root length density (RLD), average distance between roots (DBR), root soil exploration (RSE), and yield were analyzed by the statistical software Racine 2 (Chopart et al., 2008). After fitting models to the data and analysis by ANOVA, the variables and treatments were compared by Tukey's test using the SISVAR® statistical program (Ferreira, 2014).

RESULTS AND DISCUSSION

The attributes related to roots among soil tillage treatments are presented in table 3. Note that the RLD was greater when soil was subjected to a deep plowing operation followed by harrowing (WPH). This result suggests that soil operations can make the soil more penetrable, especially when lime and weed residue are incorporated. Incorporation of lime and crop residues affects nutrient availability and Al toxicity; Al saturation was high (33 %) in the 0.20-0.40 m soil layer (Table 1).

Aluminum is toxic to most plants, mainly by disrupting development of the root system (Gavassi et al., 2016). In addition, desiccation before the plowing operation contributed to incorporation of a considerable quantity of plant residue, which increases soil aeration and fertility and facilitates distribution of water to the deepest layers, resulting in a better environment for sugarcane root development.

The average DBR was highest in the no-tillage treatment (WNT), which showed no differences from the treatment where three tillage operations were made after ratoon destruction (RHPH). A big average distance between roots indicates that the roots could

Table 3. Root length density (RLD), average distance between roots (DBR), and root soil exploration (RSE) after harvest in an area of sugarcane crop renewal under different tillage operations, in the 0.00 to 0.90 m soil layer

Treatment*	RLD	DBR	RSE
	$cm\ cm^{-3}$	cm	%
WPH	0.329 a(1)	2.28 a	31.05ns
SH	0.297 b	2.35 a	28.83
WNT	0.276 b	2.56 b	26.40
WS	0.287 b	2.28 a	28.09
RDS	0.265 b	2.22 a	26.14
RHPH	0.289 b	2.41 b	28.38
DMS	0.099	0.29	7.29
CV (%)	32.82	15.48	24.98

(1) Mean values followed by different letters in the column differ statistically by soil depth by Tukey's test at 1 % significance. Treatments: WPH = weed desiccation + moldboard plowing (0.4 m) + mild spike tooth harrowing (0.15 m); SH = subsoiler (0.3 m) + mild spike tooth harrowing (0.15 m); WNT = weed desiccation + no-tillage (only furrow opening); WS = weed desiccation + subsoiler (0.4 m); RDS = ratoon destruction + subsoiler (0.40 m); RHPH = ratoon destruction + spike tooth harrowing (0.2 m) + moldboard plowing (0.4 m) + mild spike tooth harrowing (0.15 m). ns = not significant.

develop further into the soil volume. This shows that planting of sugarcane in no-tillage, after no other soil disturbance (besides furrow opening), can increase root development in a manner similar to multiple soil tillage operations. The no-till system has proven to be similar to the soil treatments that include soil tillage and this is most likely due to the soil movement necessary to open the furrows where the sugarcane is planted. However, it is expected that over the years, crop results would become similar in spite of different soil management strategies performed in the first year of the sugarcane crop.

Significant differences were observed among treatments for RLD and DBR, but no differences were detected for RSE. From this, we can infer that after 18 months of sugarcane growth, the application of lime and gypsum followed by soil fertilization provided a good environment for root development among all treatments, with no limitation to the total soil volume explored by the sugarcane root system. However, it must be considered that only a part of the sugarcane root system in contact with the fertilizer is enough for adequate nutrient uptake and satisfactory plant growth. Development of the sugarcane root system in the period prior to the first harvest is greatly affected by soil management. Soil tillage favors nutrient cycling and water and air movement in the soil and improves soil structure, allowing better development of the root system and, consequently, good sugarcane yield.

Sugarcane biomass under no-tillage or conventional tillage (plowing and harrowing), with or without lime application, was not affected, as observed by Cury et al. (2014). The authors attributed this similarity among treatments to the excellent initial soil fertility conditions. Smith et al. (2015) reported that several factors can be associated with distribution of the sugarcane root system; sugarcane genotype, plant age, soil physical and chemical properties, and water availability can directly affect root development.

The RLD was different from one soil layer to another, with the lowest density detected in the 0.20-0.40 m layer (Table 4). The significant reduction in the density of roots in this layer might be related to high Al saturation (Table 1). However, for the remaining soil layers evaluated, there was uniform root distribution throughout the soil profile.

Vasconcelos et al. (2003), studying five methodologies for root quantification in sugarcane, also identified differences in the density of roots among soil layers assessed for all the methodologies, with the uppermost layer having the greatest number of roots. However, the number of roots found by these authors below the 0.4 m depth was lower than the number found in this study. Similar results were observed by Faroni and Trivelin (2006) in assessing the root mass with active metabolism and its distribution in the soil by the isotope dilution method with ^{15}N. The differences observed in our study can be attributed to differences in soil fertility, which reduces dramatically at greater depths.

Table 4. Root length density (RLD), proportional distribution of roots (RD), average distance between roots (DBR), and root soil exploration (RSE) in sugarcane after the 1st harvest in an area of sugarcane crop renewal at different layers

Layer	RLD	DBR	RSE
m	cm cm^{-3}	cm	%
0.00-0.20	0.324 a[(1)]	2.33 a	29.89 a
0.20-0.40	0.253 b	2.68 b	24.54 b
0.40-0.60	0.279 ab	2.48 ab	27.35 ab
0.60-0.80	0.316 ab	2.25 a	30.82 a
LSD	0.073	0.28	5.34
CV (%)	32.82	15.48	24.98
Tukey significance	5 %	1 %	1 %

[(1)] Mean values followed by different letters in the columns differ by soil layers by Tukey's test.

In a study with soil texture similar to that of the present study, Azevedo et al. (2011) assessed the weight of sugarcane roots up to the depth of 1 m and identified no differences among layers because the soil fertility was high and uniform in all the soil layers studied. It seems that root growth becomes more dependent on soil fertility when soil physical properties are similar. More fertile soil, mainly with higher CEC, promotes larger quantities of sugarcane roots. About 63 % of the sugarcane root system is distributed in the first 0.5 m of soil depth, the layer with the most fertile soil (Ball-Coelho et al., 1992).

No differences were found by Azevedo et al. (2011) in root length density up to the 0.6 m soil depth. However, Costa et al. (2007), evaluating sugarcane roots between the third and fifth cut using SIARCS images in a dystrophic Oxisol (33 % sand), identified a decrease in the quantity of roots from the uppermost soil layer to the deepest, where there was a gradient of soil fertility. In this case, it should be considered that this is an extremely sandy soil, where the surface organic matter has conditioned root growth and development.

Three sugarcane post-harvest management practices were studied by Paulino et al. (2004), the authors identified that the use of a subsoiler up to the 0.15 m depth, followed by leveling by disking between rows, led to greater root length in the 0.00-0.25 m soil layer. The authors attributed these differences to better aeration and stimulation of nutrient cycling in this layer.

The values of RLD for each treatment of this study, at each layer, are illustrated in figure 1. Despite the numerical differences of this variable, there were no differences

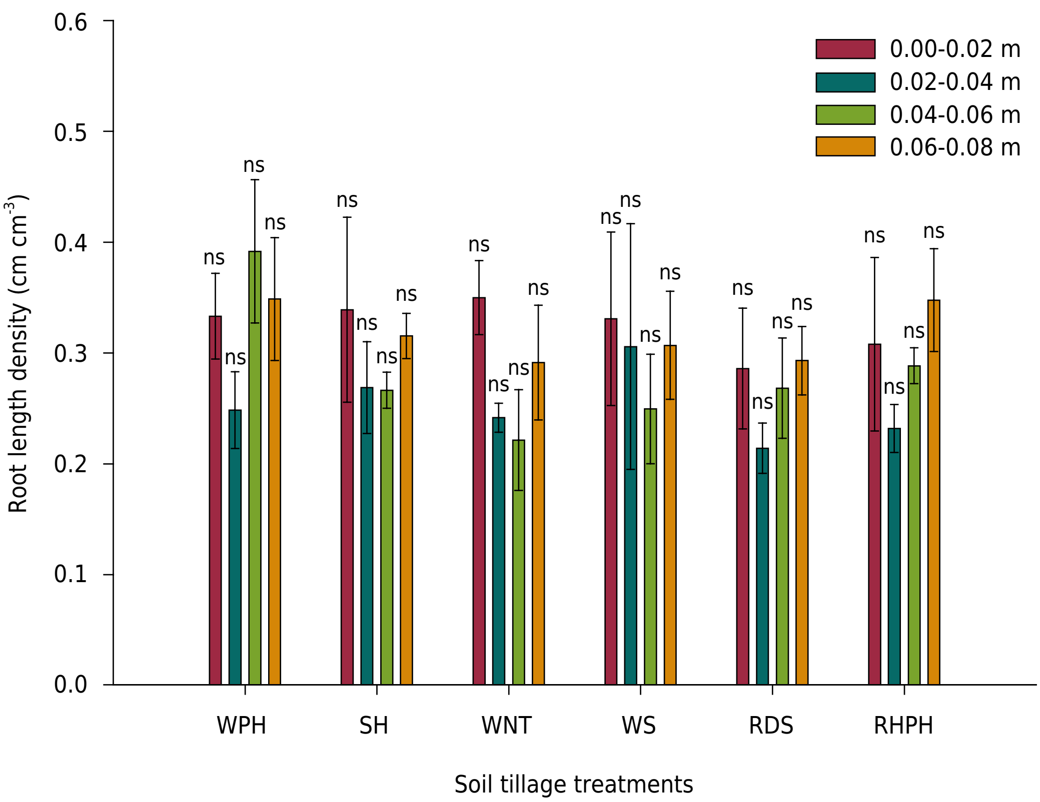

Figure 1. Root length density of sugarcane plants at different layers and under different soil tillage practices. Treatments: WPH = weed desiccation + moldboard plowing (0.4 m) + mild spike tooth harrowing (0.15 m); SH = subsoiler (0.3 m) + mild spike tooth harrowing (0.15 m); WNT = weed desiccation + no-tillage (only furrow opening); WS = weed desiccation + subsoiler (0.4 m); RDS = ratoon destruction + subsoiler (0.40 m); RHPH = ratoon destruction + spike tooth harrowing (0.2 m) + moldboard plowing (0.4 m) + mild spike tooth harrowing (0.15 m). ns = not significant differences among soil tillage treatments at each soil layer by Tukey's test at 1 % significance. CV = 32.72 %

between tillage treatments according to Tukey's test (1 % significance). It is important to emphasize that a satisfactory number of roots for development of sugarcane plants was found in all treatments at the 0.40-0.80 m layer, which was similar to the topsoil layer. These results differ from Sampaio et al. (1987), who found 75 % of the roots in the first 0.2 m soil depth. The studies that identified a greater RLD in the uppermost layers also attributed this fact to greater soil fertility in this layer.

The RLD ranged from 0.5 to 2.7 cm cm^{-3}, with small to medium values at greater depths for many South African sugarcane cultivars (van Antwerpen, 1998). In Australia, the maximum RLD value observed was 1.3 cm cm^{-3} in the surface layer, and up to 3.1 cm cm^{-3} at greater depths (Reghenzani, 1993). In the northeast region of Brazil, RLD values up to 5.3 cm cm^{-3} were found in the surface layer, due to a large quantity of organic matter in this layer (Ball-Coelho et al., 1992).

The great root quantities observed in the deepest soil layer evaluated in this study can be explained by the methodology adopted here, which considers the vertical growth of roots in the subsurface layers. Similar results were not observed by other analytic methodologies for soil profile wall like the SIARCS program employed by Vasconcelos et al. (2003).

It is noteworthy that there were no differences regarding the evaluations of root parameters at different horizontal distances in relation to the furrow (Table 5). These results are in agreement with those found by Faroni and Trivelin (2006) and Costa et al. (2007). Thus, this indicated that supplemental fertilization can be supplied up to 0.75 m from the furrow.

Sugarcane yield is shown in figure 2. In the treatments WPH and RHPH, where soil was cultivated using a moldboard plow and harrow grid, the yields were 104.87 and 105.34 t ha^{-1}, respectively. It was assumed that these two treatments facilitated lime incorporation and nutrient uptake; both increased mineralization of organic matter, which accelerates nutrient cycling. Why not be recommended the destruction of ratoon stunting disease, it is recommended to use the treatment WPH, because it takes place weed desiccation, moldboard plowing and mild spike tooth harrowing.

There was a difference of about 12 t ha^{-1} between the treatments where the soil cultivation was minimal. The use of a subsoiler increased plant survival and growth, allowing roots to reach greater depths, reducing the area of soil without plant cover, and reducing losses by erosion (Sasaki and Gonçalves, 2005; Gonçalves et al., 2016). The subsoiler was also used for the purpose of eliminating or minimizing the negative effects of soil compaction (Grotta et al., 2004). The results for sugarcane yield also

Table 5. Root length density (RLD), average distance between roots (DBR), and root soil exploration (RSE) after harvest in the area of sugarcane crop renewal at different horizontal distances from the furrow

Different horizontal distances from the furrow	RLD	DBR	RSE
	cm cm^{-3}	cm	%
0.75 m L	0.246 b[(1)]	2.67 a	24.34 b
0.45 m L	0.281 b	2.51 ab	27.39 b
Plant hole	0.360 a	2.17 c	33.06 a
0.45 m R	0.303 ab	2.38 bc	28.96 ab
0.75 m R	0.277 b	2.45 ab	27.26 b
LSD	0.066	0.27	4.89
CV (%)	28.18	13.61	21.58

[(1)] Mean values followed by different letters in the column differ statistically at distances from the furrow by Tukey's test at 1 % significance. Depth 0.75 m (0.45 to 0.75 m); 0.45 m (0.15 to 0.45 m). R = right; L = left of the plant holes.

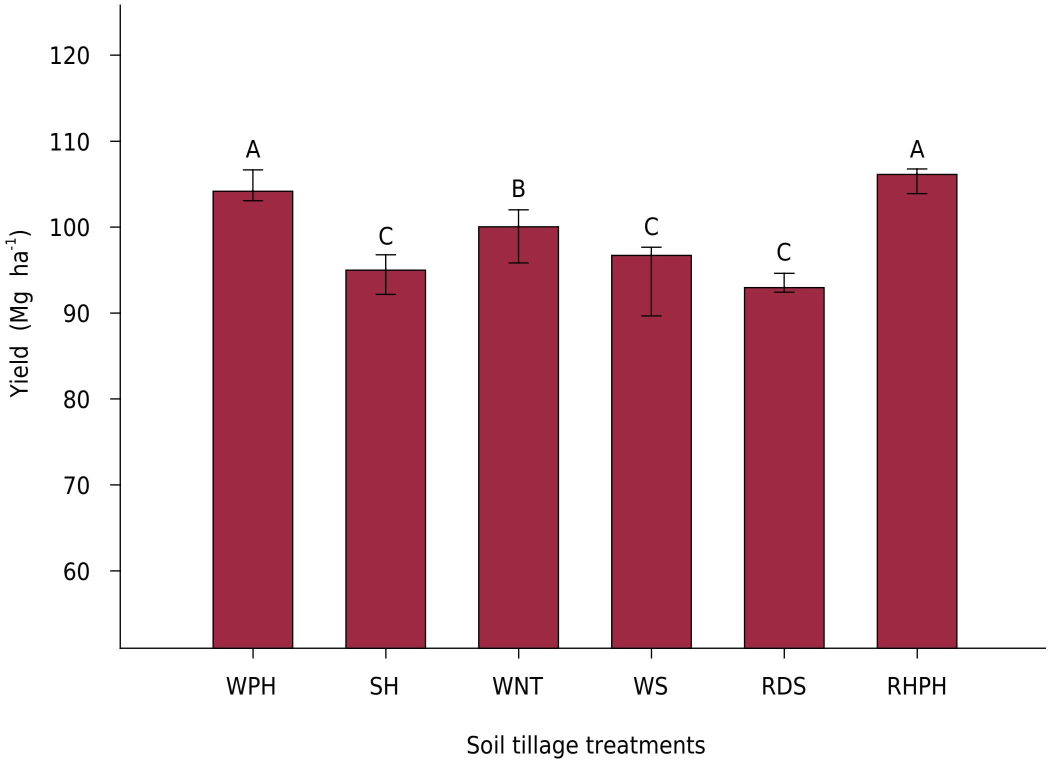

Figure 2. Sugarcane yield in the area of crop renewal under different soil preparation procedures in the Brazilian Cerrado (savanna). Treatments: WPH = weed desiccation + moldboard plowing (0.4 m) + mild spike tooth harrowing (0.15 m); SH = subsoiler (0.3 m) + mild spike tooth harrowing (0.15 m); WNT = weed desiccation + no-tillage (only furrow opening); WS = weed desiccation + subsoiler (0.4 m); RDS = ratoon destruction + subsoiler (0.40 m); RHPH = ratoon destruction + spike tooth harrowing (0.2 m) + moldboard plowing (0.4 m) + mild spike tooth harrowing (0.15 m). The same uppercase letters do not differ for soil preparation procedures by Tukey's test at 5 % significance. CV = 4.8 %.

suggest that the use of a subsoiler, even followed by harrowing, does not increase yield. No differences in yield between different soil tillage management practices were found by Paulino et al. (2004), all management practices showed intense soil movement in the surface layer. The authors attributed this response to the high sprouting vigor observed in all treatments.

Five soil tillage management practices were evaluated by Grange et al. (2005), the authors suggested that differences in yield may appear after the fifth cut. At this age of the plant, considerable uniformity among the soil management practices is already expected since the system should be stabilized. The authors identified that the subsoiler at planting can promote higher yield after the third cut, while the no-tillage treatment shows yield similar to the initial years.

Furthermore, Carvalho et al. (2010) worked with three conventional soil tillage systems and did not detect yield differences for the first 18 months, even with differences in initial root growth. They explained these similarities in the first cut to the excellent initial sprouting vigor. However, from the second cut on, the soil preparation was better when using a subsoiler. They emphasized that the no-tillage management system provided intermediate yield between the intensive soil tillage and conservational tillage using a subsoiler, which was the procedure suggested by Carvalho et al. (2010).

CONCLUSIONS

Root length density is superior for treatments that have considerable soil turnover, such as plowing at 0.4 m and harrowing at 0.15 m.

At the first sugarcane cut, sugarcane root development was similar between no-tillage and multiple soil operations.

The highest sugarcane yield in the first cut was achieved under the following management practices: weed desiccation + moldboard plowing (0.4 m) + mild spike tooth harrowing (0.15 m) (WPH); and ratoon destruction + spike tooth harrowing (0.2 m) + moldboard plowing (0.4 m) + mild spike tooth harrowing (0.15 m) (RHPH), which provided for more extensive soil tillage in the soil surface layer.

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