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LEVELS OF STRAW IN THE SOIL PHYSICAL ATTRIBUTES AND SUGAR CANE PRODUCTION IN DIFFERENT SEASONS

João Alfredo da Silva Neto[1], Sálvio Napoleão Soares Arcoverde[2]*, Cristiano Márcio Alves de Souza[3] & Cesar José da Silva[4]

1 - Agrarian Development and Rural Extension Agency, Ponta Porã, Mato Grosso do Sul, Brazil
2 - FAPED/CPAO/RAIZEN, Dourados, Mato Grosso do Sul, Brazil
3 - Federal University of Grande Dourados, Faculty of Agricultural Sciences, Dourados, Mato Grosso do Sul, Brazil
4 - Brazilian Agricultural Research Corporation (Embrapa), Dourados, Mato Grosso do Sul, Brazil

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ABSTRACT

Conservation management practices are beneficial to the physical quality of the soil and agricultural sustainability. The objective of this work was to evaluate the influence of remaining straw levels (0; 5; 10 and 15 Mg ha^{-1}) on soil physical attributes and sugarcane productivity components (third cut), in three seasons - 1 (variety RB 855156), 2 (variety RB 835486) and 3 (variety RB 835054). For physical analyses of density, macroporosity, microporosity, and total porosity, soil samples were collected in 0.00-0.05; 0.05-0.10; 0.10-0.15, and 0.15-0.20 m layers. The soil resistance to penetration (RP) was evaluated up to 0.40 m deep, at the experimental setting up (third cut), and after 12 months, following the fourth cut. The number of stems ha^{-1}, total recoverable sugar (TRS), the productivity of industrializable stalks (ISP), and sugar (TAH) were evaluated. At the end of the sugarcane harvest (first season), a reduction was found in the density and an increase in total porosity up to 0.20 m, an increase in macropores, in the 0.00-0.05 and 0.10-0.15 m layers, and RP reduction, in the 0.00-0.10 m layer. At the end of the second and third harvest seasons, RP increases of up to 0.30 m stand out. Straw levels did not influence stalk and sugar productivity in the first and second seasons, and in the third harvest season, maximum stalk and sugar productivity was obtained by maintaining 5 Mg ha^{-1} of straw.

Palavras-chave:
Cobertura
Colheita mecanizada
Cana soca
Saccharum spp.

NÍVEIS DE PALHIÇO NOS ATRIBUTOS FÍSICOS DO SOLO E PRODUÇÃO DE CANA-DE-AÇÚCAR EM DIFERENTES ÉPOCAS

RESUMO

Práticas conservacionistas de manejo são benéficas à qualidade física do solo e à sustentabilidade agrícola. Objetivou-se avaliar a influência de níveis de palhiço remanescentes (0; 5; 10 e 15 Mg ha^{-1}) sobre atributos físicos do solo e componentes de produtividade da cana-de-açúcar (terceiro corte), em três épocas - 1 (variedade RB 855156), 2 (variedade RB 835486) e 3 (variedade RB 835054). Para as análises físicas de densidade, macroporosidade, microporosidade e porosidade total coletaram-se amostras de solo nas camadas de 0,00-0,05; 0,05-0,10; 0,10-0,15 e 0,15-0,20 m. Realizou-se a avaliação da resistência do solo à penetração (RP) até 0,40 m de profundidade, no momento da instalação do experimento (terceiro corte), e após 12 meses, posteriormente ao quarto corte. Avaliaram-se o número de colmos ha^{-1}, açúcares totais recuperáveis (ATR), produtividade de colmos industrializáveis (ISP) e de açúcares (TAH). Ao final da colheita de cana (1ª época), constatou-se redução de densidade e aumento da porosidade total até 0,20 m, aumento de macroporos, nas camadas de 0,00-0,05 e 0,10-0,15 m, e redução de RP, na camada de 0,00-0,10 m. Ao final da 2ª e 3ª épocas de colheita, destacam-se os aumentos de RP até 0,30 m. Os níveis de palhiço não influenciaram a produtividade de colmos e de açúcares na 1ª e 2ª épocas e na 3ª época de colheita obteve-se produtividade máxima de colmos e de açúcares com a manutenção de 5 Mg ha^{-1} de palhiço.

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Email (corresponding author)*: salvionapoleao@gmail.com

SECTION EDITOR IN CHARGE

Michael Silveira Thebaldi

INTRODUCTION

Sugarcane is one of the main crops produced in the world, cultivated in over 100 countries. Approximately 83% of sugarcane production is concentrated in ten countries, where Brazil is the largest producer in the world, with around 37% of production, which represents 746 million tons per year (FAO, 2021).

Sugarcane is a high-energy biomass plant, in which the sugar stored in its stalk and the lignocellulosic residue remaining after sugar extraction are used for the production of biofuels or other bioproducts (Awe *et al*., 2020).

In the production of this crop in Brazil, new techniques from planting to harvesting are increasingly using intense mechanization of productive areas. The intensive traffic of machines during harvesting throughout the crop cycles is responsible for causing compaction in the soils managed in these production systems (Vischi Filho *et al*., 2017), where the water content during these mechanized operations is the primary factor responsible for maximizing impacts on soil structure along traffic lines (Guimarães Júnnyor *et al*., 2019).

In this production system, experiments whose objective is proposing conservation management practices in different edaphoclimatic environments are essential with a view to the sustainability of these systems, especially in environments with soil in physical and/or chemical restrictions and water deficit over the year. In this context, maintaining the remaining straw on the soil surface after mechanized harvesting of raw sugarcane influences some chemical, physical, and biological properties of the soil, such as the increase in the soil organic matter (Bordonal *et al*., 2018), a rise in water infiltration and conservation of water content in the soil (Santos *et al*., 2022), in addition to reducing the susceptibility to soil compaction (Castioni *et al*., 2019) as the maintenance of straw in the soil can preserve quality soil structure, which results in increased productivity and longevity of sugarcane (Silva *et al*., 2022; Arcoverde *et al*., 2023).

Maintaining intermediate amounts of the remaining straw during the sugarcane cycle brought benefits to the physical quality of the soil, while the complete removal of residues provided an increase in soil compaction, observed by the increment in soil density and resistance to penetration and reduction in the weighted average diameter of soil aggregates (Castioni *et al*., 2019).

Given the high economic and environmental costs of degraded soil recovery, it is recommended to follow the structural quality of the soil using the physical quality indicators, such as macroporosity, microporosity, total porosity, density, and resistance to soil penetration (Rossetti and Centurion, 2020); and also of the plant, such as richness in sugars and stalk and sugar productivity (Silva *et al*., 2022). Monitoring these indicators constitutes relevant information for decision-making and the selection of soil management practices inserted in sugarcane production environments to provide the appropriate balance between soil sustainability, high yields, and minimized costs (Marasca *et al*., 2016).

Thus, the objective of this work was to evaluate the influence of the levels of straw remaining from the mechanized harvesting of raw sugarcane on physical soil attributes and sugarcane productivity (third cut), at different seasons.

MATERIAL AND METHODS

The experiment was conducted on São Marcos Farm in partnership with Usina São Fernando Açúcar e Álcool, in the municipality of Dourados, state of Mato Grosso do Sul, Brazil, at an average altitude of 434 m. According to Fietz *et al*. (2017), the climate in the region, according to the Köppen-Geiger classification, is Cwa, humid mesothermal, with hot summers and dry winters. The rainfall and average monthly temperatures during the experiment are shown in Figure 1 and were obtained from the Dourados meteorological station.

The soil in the area is classified as a Oxisol (Santos *et al*., 2018). The terrain is flat, with a slope of up to 3%, and the soil is deep and has a clayey texture.

After the mechanized harvesting of third-cut raw sugarcane, three areas were demarcated for the installation of experiments (Figure 2), each corresponding to an evaluation period.

The experimental design was in randomized blocks with four straw levels and five replications, totaling 20 plots for each experimental area (harvest time). The plots consisted of six rows of sugarcane and were 15 meters long. All sampling was carried out solely in the four central lines of each plot, with the outermost lines (1 and 6) being established as lateral borders.

The results of the particle size composition of the soil in the three experimental areas corresponding to the respective evaluation seasons are shown in Table 1.

The soil chemical analyses for the characterization of the experimental areas can be seen in Table 2.

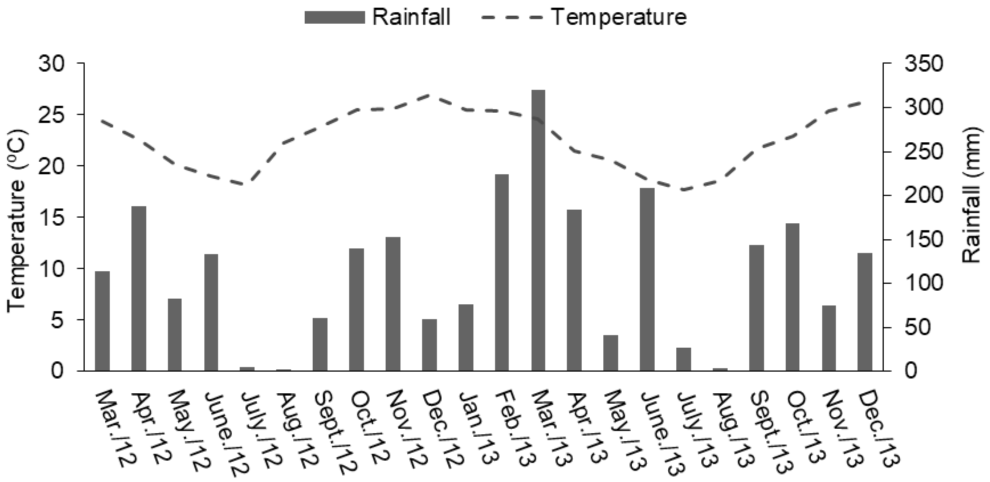

Figure 1. Rainfall and mean monthly temperature in the 2012 and 2013 crops

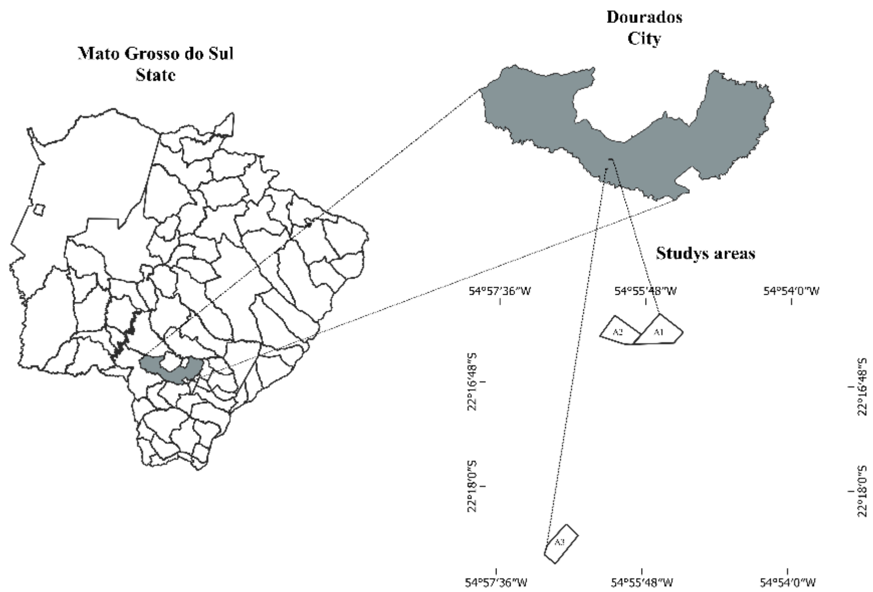

Figure 2. Location map of the experimental areas

Table 1. Particle size composition of the soil * in the three evaluation seasons

Layer	Season 1			Season 2			Season 3		
m	Clay	Silt	Sand	Clay	Silt	Sand	Clay	Silt	Sand
	g kg^{-1}								
0.00-0.05	666.0	150.0	184.0	558.0	184.0	258.0	624.0	165.0	211.0
0.05-0.10	666.0	150.0	184.0	558.0	184.0	258.0	624.0	165.0	211.0
0.10-0.20	682.0	134.0	184.0	576.0	166.0	258.0	635.0	158.0	207.0

Quantified through the pipetting method

Table 2. Soil chemical characterization in the different evaluation seasons

	Layer	pH	Ca	Mg	H+Al	K	P	SB	CEC	V	OM
	m	$CaCl_2$		Cmol dm^{-3}			Mg dm^{-3}	Cmol dm^{-3}		%	g kg^{-1}
Season 1	0.00-0.05	5.58	6.22	2.25	4.27	1.56	9.72	10.03	14.30	69.88	47.89
	0.05-0.10	5.62	6.30	2.28	4.22	1.55	9.72	10.13	14.35	70.35	46.45
	0.10-0.20	5.45	5.30	2.00	5.45	1.03	5.06	8.33	13.78	63.28	39.39
Season 2	0.00-0.05	4.58	2.31	0.86	7.76	1.50	5.57	4.67	12.43	37.88	36.03
	0.05-0.10	4.53	2.04	0.71	8.16	1.37	4.24	4.11	12.28	34.11	32.58
	0.10-0.20	4.44	1.70	0.55	8.47	1.14	2.90	3.39	11.86	29.16	28.95
Season 3	0.00-0.05	5.24	4.23	1.27	4.14	0.85	5.96	6.36	10.50	60.60	37.06
	0.05-0.10	5.25	4.09	1.25	4.32	0.65	4.84	5.99	10.31	57.87	35.19
	0.10-0.20	5.07	3.17	1.06	4.88	0.43	3.04	4.66	9.54	48.64	30.85

The experiments consisted of three harvest seasons, each season with a different variety of sugar cane depending on the maturation cycle. In the area harvested in the first season, on May 02, 2012, the early cycle variety RB 855156 was grown and straw levels were established on May 07, 2012; After 12 months, on May 21, 2013, the sugarcane was harvested again for final evaluation. In the area harvested in the second season, on August 08, 2012, the intermediate maturity cycle variety RB 835486 was cultivated and the straw levels were established on August 15, 2012; after 12 months, on August 14, 2013, the sugarcane was harvested again for final evaluation. In the area harvested in the third season, on November 20, 2012, the late maturation cycle variety RB 835054 was grown and the straw levels were established on November 27, 2012; after 9.5 months, on September 10, 2013, the sugarcane harvest was carried out again for final evaluation, and this was brought forward due to the strong frosts.

After harvesting at the beginning of the experiment, before the application of the treatments, the amount of straw in the area was evaluated, where average values of 15.20 Mg ha^{-1} were found in season 1; 18.64 Mg ha^{-1} in season 2 and 17.10 Mg ha^{-1} in season 3. After the bundling operation, the straw was completely removed from the area and returned later with the mass values (levels) stipulated for each plot.

In each experimental area, straw was bundled and three levels of straw (5; 10, and 15 Mg ha^{-1}) and the control treatment (0 Mg ha^{-1}) were maintained on the ratoons, with total straw collection. After setting up these treatments, the experimental area received the same management as the commercial areas of the plant, where weeds were controlled through the application of herbicides and manual weeding; fertilization was carried out using 380 kg ha^{-1} of ammonium nitrate and 360 m^3 ha^{-1} of vinasse through fertigation, split into three applications of 120 m^3 ha^{-1} with an interval of three to five days between applications.

The set of machines used to rake the straw was a rake with four wheels with a diameter of 145 cm and 40 flexible teeth per wheel, driven by contact between the wheels and the straw, coupling at three points, without the need for a power take-off, vertical movement of the equipment through hydraulic drive, pulled by a John Deere tractor, model 6165J with 165 hp of power.

In all experimental plots, soil samples with preserved structure were collected in metallic cylinders (volumetric rings) with 5.57 cm in diameter and 4.1 cm in height, in 1 0.00-0.05; 0.5-0.10; 0.10-0.15 and 0.15-0.20 m layers. Soil collections were carried out after harvesting the sugar cane at the experiment (initial) setting up and after harvesting, 12 months after its installation (final). Subsequently, the soil samples were sent to the laboratory to determine macroporosity, microporosity, total porosity, and soil bulk density (Teixeira *et al*., 2017). Soil resistance to penetration (RP) was determined using a Falker PLG 1020 electronic penetrometer, with an automatic data acquisition system up to a depth of 0.40 m, where five replications were carried out per plot. Along with the RP determinations, soil sampling was carried out with the aid of a Dutch auger in 0.00-0.10; 0.10-0.20; 0.20-0.30, and 0.30-0.40 m layers to determine gravimetric soil moisture (Teixeira *et al.*, 2017).

To evaluate the influence of treatments on the growth and production of sugarcane, 12 months after harvest, the number of stalks ha^{-1}, total recoverable sugar (RRS), the productivity of industrializable stalks (ISP) and sugars (TAH) were quantified. The number of culms was obtained by counting them, in three central lines of five meters, respecting the borders and, using a simple rule of three, estimating the number of culms ha^{-1}. In the central rows of each plot, three subsamples of 10 canes were collected, with the mass of these subsamples and the number of stalks ha^{-1}, a simple rule of three was applied to obtain stalk productivity (ISP). Sugar productivity (TAH) was estimated by multiplying the total reducing sugar (TRS) data by the ISP results, in each plot. The determination of TRS values was carried out through technological quality analysis, according to the current methodology in the SPCTS (Sugarcane Payment System, by Sucrose Content) described in Fernandes (2003).

Data were subjected to analysis of variance, when significant at 5% probability, the means of the physical attributes of the soil were compared using the test of Tukey ($p \leq 0.05$), while the means of the sugarcane productivity components sugar were subjected to regression analysis ($p \leq 0.05$). The analyses were carried out using the statistical program SIRVAR® (Ferreira, 2014).

RESULTS AND DISCUSSION

Soil bulk density in the area harvested at the beginning of the crop (season 1) was not influenced by the levels of straw in the soil in all layers, nor was there any interaction between straw levels and the moment in which the assessments were carried out in all layers (Table 3). However, a reduction in soil densities was observed in all layers when comparing the average straw levels in the initial and final assessment (12 months after straw application).

For the area harvested in the middle of the harvest (season 2), there was an interaction between straw levels and the moment in which the assessments were carried out, in the 0.15-0.20 m layer, in which with the maintenance of 10 Mg ha^{-1} of straw, a decrease in soil density was observed from 1.36 g cm^{-3} to 1.27 g cm^{-3}, after one year of evaluation, a similar result when comparing the average levels of straw in the same layer, whose average reduction went from 1.34 g cm^{-3} to 1.29 g cm^{-3}, after one year of evaluation (Table 3).

In the area harvested at the end of the harvest (season 3), an interaction was observed between straw levels and assessments for the 0.00-0.05 and 0.15-0.20 m layer, demonstrating a reduction in density from the initial assessment for the final, when all the straw was removed in both layers. Nevertheless, when 15 Mg ha^{-1} of straw was added, the soil density increased after one year, in the 0.15-0.20 m layer. It was also observed, for the final evaluation (season 3), that there was greater soil density in the 0.15-0.20 m layer when 15 Mg ha^{-1} of straw was applied (Table 3).

It is pointed out that, based on the results mentioned above, no effect of cultural treatments and sugarcane harvesting in the area harvested in the middle of the harvest (season 2) was observed. On the other hand, in areas harvested at the beginning (season 1) and end (season 3) of the harvest, a reduction in soil bulk density in the surface layers was observed, in the mean of the treatment of sugarcane straw levels, except in the 0 to 0.05 m layer for season 3. These results may be associated with the positive effect of straw on the soil in maintaining soil moisture for longer, which is considered one of the main factors responsible for the root growth of sugarcane (Cury *et al.*, 2014; Clemente *et al.*, 2017), and inversely and linearly influence the density and resistance of the soil to penetration (Sá *et al.*, 2016). Furthermore, the presence of straw on the soil surface can create conditions for part of the compaction energy produced by machinery traffic to be dampened before contact with the soil (Cherubin *et al.*, 2021).

Straw-covered soil can minimize the effect of sugarcane harvester traffic, as it withstands greater pressures, compared to those without crop residues (Garbiate *et al.*, 2011). The sugarcane straw deposited on the soil attenuates the applied loads and dissipates the compaction energy by up to 30% (Braida *et al.*, 2006); however, these effects do not seem to be immediate in the density of clayey textured soils, as it is seen in the three areas evaluated in this work. These results can be better

Table 3. Means of soil bulk density (g cm^{-3}) in the 0.00-0.05; 0.05-0.10; 0.10-0.15; 0.15-0.20 m layer, for three seasons and in two evaluations (initial and final)

	Doses of straw (Mg ha^{-1})	Layer (m)							
		0.00 – 0.05		0.05 – 0.10		0.10 – 0.15		0.15 – 0.20	
		Initial	Final	Initial	Final	Initial	Final	Initial	Final
Season 1	0	1.47	1.35	1.49	1.41	1.42	1.36	1.33	1.30
	5	1.48	1.42	1.52	1.44	1.45	1.38	1.37	1.34
	10	1.49	1.44	1.50	1.48	1.48	1.42	1.37	1.37
	15	1.50	1.44	1.50	1.46	1.42	1.40	1.37	1.34
	Mean	1.49a	1.41b	1.50a	1.45b	1.44a	1.39b	1.36a	1.33b
Season 2	0	1.42	1.38	1.46	1.40	1.39	1.35	1.35a	1.29a
	5	1.36	1.38	1.39	1.41	1.34	1.36	1.31a	1.33a
	10	1.36	1.39	1.35	1.37	1.31	1.32	1.36a	1.27b
	15	1.37	1.36	1.37	1.36	1.35	1.37	1.32a	1.28a
	Mean	1.38	1.38	1.39	1.39	1.35	1.35	1.34a	1.29b
Season 3	0	1.39a	1.31b	1.41	1.33	1.40	1.32	1.33a	1.24Bb
	5	1.34a	1.36a	1.42	1.40	1.39	1.34	1.33a	1.28ABa
	10	1.40a	1.43a	1.42	1.39	1.36	1.34	1.30a	1.27ABa
	15	1.35a	1.39a	1.41	1.42	1.37	1.36	1.29b	1.35Aa
	Mean	1.37	1.37	1.41a	1.38b	1.38a	1.34b	1.31a	1.29b

Initial: collection at treatment setting up; Final: collection after mechanized harvesting of sugar cane after one year. Season 1 (early cycle sugarcane, harvested at the beginning of the crop); Season 2 (intermediate-cycle sugarcane, harvested in the middle of the crop); Season 3 (Late cycle sugarcane, harvested at the end of the crop). Means followed by equal letters, capital letters in the column, comparing doses of straw in each evaluation (initial and final) and the means of the evaluations for each period and lowercase letters in the line, comparing evaluation in each dose of straw and the evaluations in the means of the doses of straw for each season, do not differ from each other using the test of Tukey, at 5% probability

understood by the fact that the evaluations were carried out in a single harvest, in the third ratoon, in a cohesive soil and which, therefore, did not suffer the significant effects of compression caused by machinery traffic, possibly because of the high capacity of load support of this soil. Although the straw layer can affect the intensity and propagation of compression that reaches the soil surface, the cushioning effect of straw may be insufficient to reduce the risk of soil compaction in sugarcane fields, especially when there is machinery traffic that transmits high pressures in loose soils and/or with lower load-bearing capacity (Cherubin *et al*., 2021).

As for soil density, depending on straw levels and evaluation seasons, values less than the range between 1.51 and 1.59 Mg m^{-3} were observed in all layers. The limits of this range are considered maximum by Sá *et al*. (2016) and Oliveira *et al*. (2012) when evaluating compaction in Oxisols with clayey to very clayey texture, respectively. These results were also observed by Arcoverde *et al*. (2019b) when evaluating the cultivation of sugar cane, in plant cane, in a Oxisol, in no-tillage and reduced tillage systems.

The analyses of the macroporosity values showed that for season 1, there was no interaction between straw levels and evaluations, with an effect on the means of the evaluations for the 0.00-0.05 and 0.10-0.15 m layers, in which the macroporosity values increased from the initial to the final assessment (Table 4).

It can be seen that for season 2, for the 0.05-0.10 and 0.15-0.20 m layers, there was an interaction between straw levels and evaluations, where a reduction from the initial to the final evaluation was observed when it was applied 5 Mg ha^{-1} of straw (Table 4).

Regarding season 3, there was an interaction between straw levels and seasons, in the 0.15-0.20 m layer, where an increase in macropores was found from the initial to the final assessment for doses of 0; 5, and 10 Mg ha^{-1} of straw. Likewise, in the means of the straw levels, it is observed that an increase in macropores after 9.5 months of the experimental conduction in the area harvested at the end of the crop in the 0.05-0.10, 0. 10-0.15 and 0.15-0.20 m layers (Table 4).

Table 4. Means of soil macroporosity (%) in the 0.00-0.05; 0.05-0.10; 0.10-0.15; 0.15-0.20 m layer, for the three seasons and in two evaluations (initial and final)

	Doses of straw (Mg ha^{-1})	Layer (m)							
		0.00 – 0.05		0.05 – 0.10		0.10 – 0.15		0.15 – 0.20	
		Initial	Final	Initial	Final	Initial	Final	Initial	Final
Season 1	0	5.28	6.92	5.61	6.84	6.90	7.62	8.45	8.32
	5	4.41	5.13	4.37	5.21	5.52	6.54	6.63	7.66
	10	4.62	6.17	4.79	4.99	5.08	6.37	6.83	6.62
	15	3.89	4.98	5.47	5.47	6.39	7.07	7.48	8.08
	Mean	4.55b	5.80a	5.06	5.63	5.97b	6.90a	7.35	7.67
Season 2	0	8.52	6.60	7.44a	6.94a	8.41	7.63	8.97a	8.91a
	5	10.53	8.04	9.86a	7.12b	9.82	8.13	10.02a	7.84b
	10	9.40	7.06	9.02a	8.41a	9.22	9.02	8.70a	9.82a
	15	8.91	9.61	7.15a	8.43a	7.24	8.97	7.80a	9.29a
	Mean	9.34	7.83	8.37	7.73	8.67	8.44	8.87	8.97
Season 3	0	7.93	9.51	5.59	8.54	5.03	7.65	6.35b	9.72a
	5	10.26	8.29	6.61	6.63	5.93	7.41	6.20b	8.54a
	10	6.58	7.73	4.50	7.22	6.01	8.31	7.05b	10.07a
	15	7.89	8.79	5.33	6.72	5.93	6.91	7.59a	8.22a
	Mean	8.17	8.58	5.64b	7.28a	5.72b	7.57a	6.80b	9.14a

Initial: collection at the treatment setting up; Final: collection after mechanized harvesting of sugar cane after one year. Season 1 (early cycle sugarcane, harvested at the beginning of the crop); Season 2 (intermediate cycle sugarcane, harvested in the middle of the crop); Season 3 (Late cycle sugarcane, harvested at the end of the crop). Means followed by equal letters, capital letters in the column, comparing doses of straw in each evaluation (initial and final) and in the means of the evaluations for each season and lowercase letters in the line, comparing evaluation in each dose of straw and the evaluations in the means of the doses of straw for each season, do not differ from each other using the test of Tukey, at 5% probability

It is important to observe that the values of soil macroporosity obtained in this work (Table 4) are less than 0.10 $m^3 m^{-3}$, which is the minimum suitable for liquid and gaseous exchange between the external environment and the soil, and considered critical for the growth of the roots in most crops, as Rossetti and Centurion (2013) emphasize.

Considering the average straw doses, it was observed that microporosity had lower values in the final evaluation in all layers for seasons 1 and 3 and in the 0.15-0.20 m layer for season 2 (Table 5). In season 1 (0.10-0.15 and 0.15-0.20 m layers), when analyzing the levels of straw levels between assessment seasons, a decrease in micropores was generally observed in the final assessment, with the treatment without straw showing the lowest macropore value, compared to the 10 Mg ha^{-1} dose in the 0.15-0.20 m layer. Large amounts of straw maintained in the soil can subtly increase the load-bearing capacity and thus improve the stability of that soil structure (Cherubin *et al*., 2021). For season 2, there was an interaction between straw levels and evaluations in the 0.05-0.10 and 0.15-0.20 m layers, where a reduction in micropores was observed with the total removal of straw and, in average levels of straw levels after one year of evaluation.

An interaction was found between the levels of straw and the evaluations for season 1 in the 0.10-0.15 and 0.15-0.20 m layers, where the micropore values were reduced in all straw levels after one year. On the other hand, in season 3, the interaction between the levels of straw and evaluations occurred in 0.05-10; 0.10-0.20, and 0.15-0.20 m layers, where a reduction in micropores was observed in the first two, after one year of evaluation. It should be observed that, in the mean of straw levels, as well as at the beginning of the harvest (season 1), a decrease was found in the micropores, after one year of evaluation, in all layers (Table 5). These results corroborate those found by Arcoverde *et al*. (2019b) when working with a Oxisol cropped with sugar cane, who found a reduction in microporosity resulting from compaction caused by machinery traffic in the area during the sugarcane-plant cycle. These authors also found that, after machinery traffic, there was a reduction in macroporosity, an increase in microporosity, and, as a consequence, an increase in the total porosity of the soil, with microporosity values greater than 0.40 m^3 m^{-3} and macroporosity values below 0.10 m^3m^{-3}, similar to the values observed in this work.

An interaction was observed between the straw levels and the evaluations for season 1, in the 0.05-10, 0.10-0.15, and 0.15-0.20 m layers, wherein the first two layers, reduced the values of porosity for all straw levels evaluated after one year. The same result occurred in the last layer, except for the levels of 5 and 10 Mg ha^{-1} (Table 6). According to Arcoverde *et al*. (2023), in a Oxisol, they found that maintaining 100% remaining straw increased the organic matter content in the surface layer. On the other hand, in soils with a lower organic matter content, the continuous removal of straw over several sugarcane cuts results in an increase in density and a reduction in soil macroporosity (Castioni *et al*., 2019).

Concerning season 2, there was an interaction between straw levels and evaluations, in the 0.05-0.10 m layer, with a reduction in porosity values for all evaluated levels and, in the 0.15-0 m layer, 20 m, for the dose of 5 Mg ha^{-1} there was a reduction in soil porosity after one year. This was repeated for season 3, in the 0.00-0.5 m layer (Table 6).

It is highlighted that, on the mean of straw levels, there was a reduction in total porosity values after one year of evaluation, in all layers, at season 1, and in the 0.05-0.10 and 0.10- 0.15 layers, in season 2; finally, no significant difference was observed in season 3 (Table 6).

Soils must have a minimum total porosity of 30% for root growth, with the ideal soil showing 50% of its total volume as porous space (Camargo; Alleoni, 1997). Therefore, the soil analyzed in this work falls within the limit of 50% indicated as ideal. The effect of several years of sugarcane cultivation was observed by Souza *et al*., (2006) when they concluded that, in soils with longer cultivation time, porosity decreased due to the effects caused by the management. Even though it was only one year of cultivation, the reduction in porosity for seasons 1 and 2, observed in this experiment, can be attributed to the reduction

Table 5. Means of soil microporosity (%) in the 0.00-0.05; 0.05-0.10; 0.10-0.15; 0.15-0.20 m layer for the three seasons and two evaluations (initial and final)

	Doses of straw (Mg ha^{-1})	Layer (m)							
		0.00 – 0.05		0.05 – 0.10		0.10 – 0.15		0.15 – 0.20	
		Initial	Final	Initial	Final	Initial	Final	Initial	Final
Season 1	0	44.88	43.45	44.55	41.40	44.36a	41.42b	44.38a	41.16Bb
	5	46.90	43.79	46.13	43.31	45.75a	42.41b	45.33a	43.4ABb
	10	46.66	43.75	46.08	43.30	45.88a	43.01b	45.05a	44.19Aa
	15	46.87	45.12	45.99	43.45	45.44a	42.99b	45.73a	43.45ABb
	Mean	46.33a	44.03b	45.69a	42.87b	45.36a	42.46b	45.12a	43.05b
Season 2	0	44.07	44.79	44.75a	43.19b	44.54	43.32	44.94a	43.56b
	5	43.37	44.29	43.46a	44.11a	43.66	43.16	43.72a	44.15a
	10	42.55	43.74	42.68a	42.75a	42.71	42.55	43.60a	43.15a
	15	43.02	42.84	43.22a	42.47a	44.12	38.69	44.21a	43.61a
	Mean	43.25	43.92	43.53	43.13	43.76	41.93	44.12 a	43.62b
Season 3	0	43.79	41.64	44,69a	41.65b	45.78a	42.63b	45.91a	41.67Ba
	5	43.07	42.18	44,28a	43.3a	44.8a	43.47a	45.06a	43.25ABa
	10	43.96	43.17	44,88a	42.56b	44.6a	43.29a	45.35a	43.15ABa
	15	43.56	43.31	43,81a	43.75a	44.88a	44.47a	44.74a	44.35Aa
	Mean	43.60a	42.58b	44,42a	42.82b	45.02a	43.47b	45.27a	43.11 b

Initial: harvesting at the treatment setting up; Final: collection after mechanized harvesting of sugar cane after one year. Season 1 (early cycle sugarcane, harvested at the beginning of the crop); Season 2 (intermediate cycle sugarcane, harvested in the middle of the crop); Season 3 (Late cycle sugarcane, harvested at the end of the crop). Means followed by equal letters, capital letters in the column, comparing Evaluation in each dose of straw (initial and final) and the average evaluations for each period and lowercase letters in the line, comparing evaluation in each dose of straw and the evaluations in the mean of the doses of straw for each season, do not differ from each other using the test of Tukey, at 5% probability

Table 6. Means of total soil porosity (%) in the 0.00-0.05; 0.05-0.10; 0.10-0.15; 0.15-0.20 m layer, for the three seasons and two evaluations (initial and final)

	Doses of straw (Mg ha^{-1})	Layer (m)							
		0.00 – 0.05		0.05 – 0.10		0.10 – 0.15		0.15 – 0.20	
		Initial	Final	Initial	Final	Initial	Final	Initial	Final
Season 1	0	50.15	50.37	50.16a	48.25b	51.26a	49.04b	52.83a	49.48b
	5	51.31	48.92	50.50a	48.52b	51.27a	48.95b	51.95a	51.06a
	10	51.29	49.92	50.87a	48.30b	50.95a	49.38b	51.87a	50.82a
	15	50.76	50.10	51.45a	49.01b	51.84a	50.06b	53.21a	51.53b
	Mean	50.88a	49.83b	50.75a	48.52b	51.33a	49.36b	52.47a	50.72b
Season 2	0	52.59	51.39	52.19a	50.14b	52.95	50.95	53.91a	52.48a
	5	53.90	53.34	53.33a	51.23b	53.48	51.29	53.73a	51.98b
	10	51.95	50.80	51.70a	51.16b	51.92	51.57	52.3a	52.97a
	15	51.93	52.45	50.38a	50.90b	51.35	47.65	52.01a	52.9a
	Mean	52.59	52.00	51.90a	50.86b	52.43a	50.37b	52.99	52.58
Season 3	0	51.71a	51.55a	50.28	50.19	50.81	50.29	52.26	51.39
	5	53.34a	50.47b	50.89	49.93	50.73	50.87	51.26	51.78
	10	50.54a	50.90a	49.88	49.78	50.58	51.60	52.40	53.23
	15	51.45a	52.09a	49.14	50.47	50.81	51.37	52.33	52.58
	Mean	51.76a	51.25a	50.05	50.09	50.73	51.03	52.06	52.25

Initial: harvesting at the treatment setting up; Final: harvesting after mechanized harvesting of sugar cane after one year. Season 1 (early cycle sugarcane, harvested at the beginning of the crop); Season 2 (intermediate cycle sugarcane, harvested in the middle of the crop); Season 3 (Late cycle sugarcane, harvested at the end of the crop). Means followed by equal letters, capital letters in the column, comparing doses of straw in each evaluation (initial and final) and the means of the evaluations for each period and lowercase letters in the line, comparing evaluation in each dose of straw and the evaluations in the average doses of straw for each season, do not differ from each other using the test of Tukey, at 5% probability

presented by microporosity, that is, in clay soil the total porosity is conditioned by the high clay content, as observed by Arcoverde *et al*. (2019b) when evaluating a Oxisol with a clayey texture up to 0.20 m deep.

As for soil moisture, no differences were found among treatments and evaluations (Table 7), which constitutes an important factor in the comparison of penetration resistance values as moisture levels significantly interfere with soil resistance results to penetration.

Table 8 shows the values of soil resistance to penetration. A significant interaction was observed between straw levels and evaluation seasons for season 1, in the 0.00-0.10 m layer; for season 2, in all layers; and for season 3, in the 0.00-0.10 and 0.10-0.20 m layer. It should be seen that the evaluated straw levels did not influence the resistance to soil penetration (RP) for seasons 1 and 2 in all layers and in 0.10-0.20, 0.20-0.30, and 0.30-0.40 m layers for season 3 (Table 8). The levels of straw had a significant effect only for season 3, harvested at the beginning of the crop, in the 0.00-0.10 m layer, where a reduction in RP can be observed with the maintenance of 15 Mg ha^{-1} of straw compared to other levels.

The comparison between the initial and final assessments on average straw levels showed that after one year, a 32.8% reduction in RP was found for season 1 in the 0.0-0.10 m layer, which can be attributed to lower soil density in this layer (Table 4). For season 2, in all layers, there was an increase in RP values from the initial to the final assessment, which may be related to the reduction in macroporosity in the superficial layer (Table 5) and factors intrinsic to the soil at depth. On the other hand, in season 3, it is observed the fact that, in the layers of 0.00-0.10 and 0.10-0.20 m, a reduction in RP occurs with the maintenance of 15 Mg ha^{-1} of straw in the soil. It should be observed that soil resistance to penetration is directly related to soil density and these are attributes constantly used to evaluate the structural quality of the soil (Rossetti and Centurion, 2020) and related to the performance of the main crops, such as sugarcane (Arcoverde *et al*., 2019a; Arcoverde *et al*., 2019c), soybeans (Arcoverde *et al*., 2022) and corn (Rossetti and Centurion, 2020).

Table 7. Means for soil moisture (%) in the 0.00-0.10; 0.10-0.20; 0.20-0.30; 0.30-0.40 m layers for three seasons

	Level of straw (Mg ha^{-1})	Layer (m)			
		0.00 – 0.05	0.05 – 0.10	0.10 – 0.15	0.15 – 0.20
Season 1	0	28.43	28.57	28.59	28.59
	5	28.79	28.60	28.60	28.62
	10	31.96	32.10	32.13	32.10
	15	31.49	31.78	31.68	31.75
Season 2	0	28.97	28.85	28.88	28.82
	5	30.84	30.40	30.62	30.48
	10	30.62	30.70	30.74	30.73
	15	30.92	31.00	31.03	30.98
Season 3	0	29.21	29.35	29.45	29.39
	5	30.55	30.67	30.86	30.74
	10	31.43	31.52	31.43	31.48
	15	32.37	32.24	32.11	32.08

Season 1 (Early-cycle sugar cane, harvested at the beginning of the crop); Season 2 (Intermediate cycle sugar cane, harvested in the middle of sugar cane); Season 3 (Late-cycle sugar cane, harvested at the end of the crop)

Table 8. Means of soil resistance to penetration (MPa) in 0.00-0.10, 0.10-0.20; 0.20-0.30; 0.30-0.40 m layers, for three seasons and in two assessments (initial and final)

	Doses of straw	Layer (m)							
	Mg ha^{-1}	0.00 – 0.10		0.10 – 0.20		0.20 – 0.30		0.30 – 0.40	
		Initial	Final	Initial	Final	Initial	Final	Initial	Final
Season 1	0	2.14a	1.44b	2.62	2.67	2.51	2.51	2.14	2.10
	5	1.98a	1.50b	2.59	2.71	2.58	2.61	2.40	2.26
	10	2.09a	1.29b	2.64	2.62	2.57	2.55	2.29	2.23
	15	1.96a	1.28b	2.66	2.48	2.51	2.56	2.10	2.22
	Mean	2.04a	1.37b	2.63	2.62	2.54	2.56	2.23	2.19
Season 2	0	1.41b	1.74a	2.54b	2.87a	2.37b	3.02a	2.32b	2.85a
	5	1.40b	1.81a	2.32b	2.88a	2.23b	2.85a	2.14b	2.79a
	10	1.22b	1.82a	2.25b	2.77a	2.20b	2.89a	2.10b	2.73a
	15	1.23b	1.82a	2.40b	2.88a	2.37b	2.99a	2.23b	2.83a
	Mean	1.32b	1.80a	2.38b	2.85a	2.29b	2.94a	2.20b	2.80 a
Season 3	0	1.64Aa	1.71a	2.67b	2.93a	2.37	2.52	2.19	2.16
	5	1.68Aa	1.62a	2.80a	2.81a	2.39	2.42	2.19	2.08
	10	1.47Aba	1.58a	2.64a	2.86a	2.38	2.46	2.06	2.17
	15	1.15Bb	1.63a	2.48b	2.88a	2.42	2.63	2.18	2.20
	Mean	1.49b	1.64a	2.65b	2.87a	2.39b	2.48a	2.15	2.15

Initial: collection at the treatment setting up; Final: collection after mechanized harvesting of sugar cane after one year. Season 1 (early cycle sugarcane, harvested at the beginning of the crop); Season 2 (intermediate cycle sugarcane, harvested in the middle of the harvest); Season 3 (Late cycle sugarcane, harvested at the end of the crop). Means followed by equal letters, capital letters in the column, compare doses of straw in each evaluation (initial and final) and the means of the evaluations for each period and lowercase letters in the line, comparing evaluation in each dose of straw and the evaluations in the average doses of straw for each season, do not differ from each other by the test of Tukey, at 5% probability

Values of RP greater than 2 MPa are considered high for Oxisols and this value is accepted as a critical limit for the development of the plant root system (Tormena *et al*., 1998). However, as sugarcane is a more tolerant crop and has a more aggressive root system, values greater than 2 MPa are considered restrictive to sugarcane root growth, with 3.0 MPa in clayey soils (Souza *et al*., 2015) and 3.8 MPa in very clayey soils (Sá *et al*., 2016).

Regarding the growth and productive variables of sugarcane, there was no influence of straw levels on the number of stalks ha^{-1}, 12 months after harvest, in the three evaluation periods (Figure 3A). In seasons 3 and 1, respectively, an average of 85,391 and 84,318 stalks ha^{-1} was observed, and in season 2, a lower number of stalks ha^{-1} was observed. These results demonstrate good adaptation of the cultivar RB 855156 (season 1) to mechanized harvesting of raw sugarcane with the maintenance of straw over the ratoon, which combined with harvesting at the beginning of the season (good humidity and soil temperature), application of 360 m^3 of vinasse through fertigation, it had intense and rapid initial tillering. These characteristics of rapid and intense tillering in a mechanized raw sugarcane harvesting system can be attributed to factors such as more vigorous ratooning, earlier cultivar, and low sensitivity of the cultivar to the presence of straw or climatic conditions. Concerning the harvest at the beginning of the season (season 1), the mid-season harvest (season 2), in an area cultivated with RB 835486, showed a lower number of stalks ha^{-1} and slower tillering, probably due to less water availability and temperature at the time of ratoon sprouting (Figure 1) and lower soil fertility in this plot (Table 2). For the harvest at the end of the season (season 3), at 9.5 MH, there was no difference in the number of stalks ha^{-1} between straw levels from 0 to 15 Mg ha^{-1} of straw, at 9.5 MH when cultivar RB 835054 showed greater sensitivity to the presence of greater amounts of residual straw during the ratoon sprouting period, which resulted in lower tillering. However, it should be observed that this was not a limiting factor for the establishment of the sugarcane plantation, as at 9.5 MH, on average, there were 12.8 industrializable stalks per meter.

For the Total Recoverable Sugar (TRS) content, no significant effect of straw levels for the three seasons (Figure 3B) was found. However, the lowest TRS value stands out in season 3, which can be attributed to the late variety and, above all, to the influence of frost on the plants, causing them to be harvested earlier and, therefore, accumulating less sugar in the stalk.

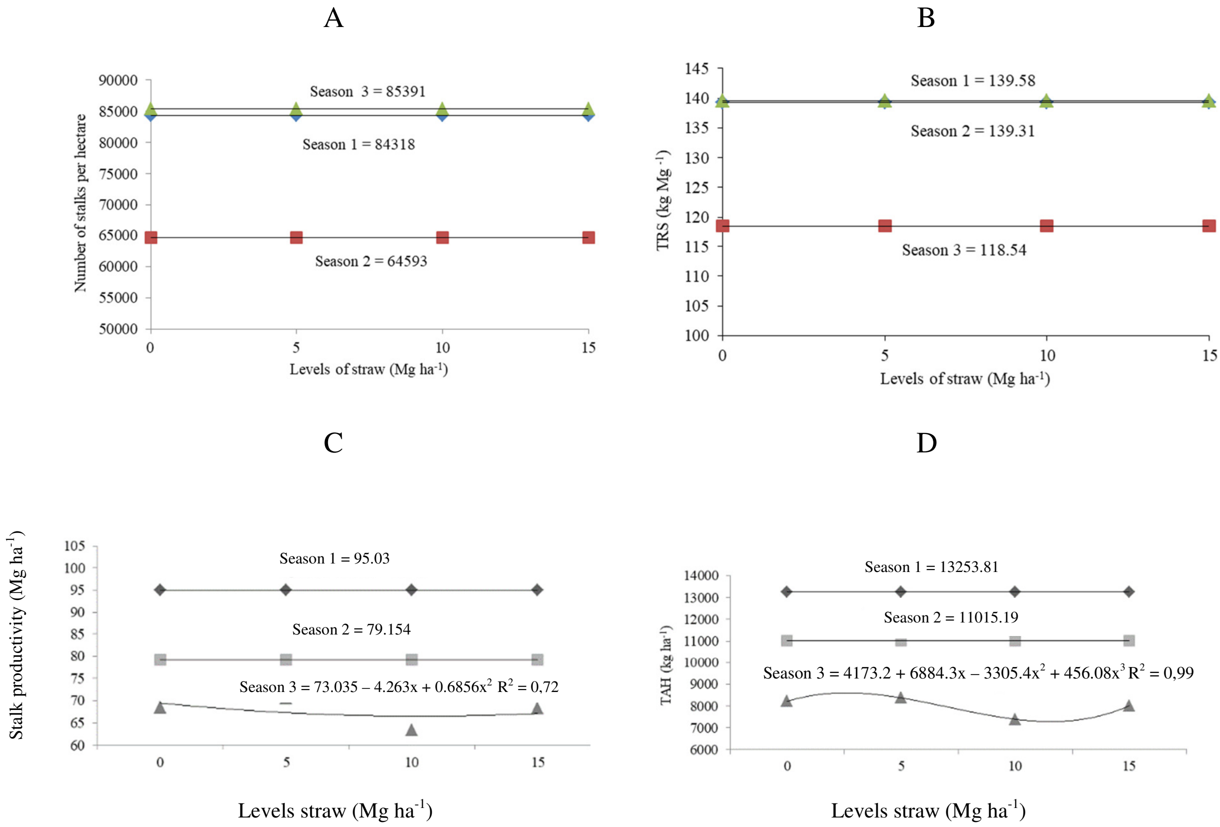

Figure 3. Number of sugarcane stalks per hectare (A), total reducing sugars – TRS (B), stalk productivity – ISP (C) , and sugar productivity – TAH (D) subjected to the respective straw levels, for the seasons 1 (RB 85 5156), 2 (RB 835486) and 3 (RB 83 5054), evaluated 12 months after mechanical harvesting (MH)

The levels of straw did not influence the estimate of stalk productivity (ISP) in seasons 1 and 2, while in season 3, there were direct responses to different straw levels, with the highest estimated productivity (70.50 Mg ha^{-1}) achieved when 5 Mg ha^{-1} of straw was applied (Figure 3C).

Sugar productivity (TAH) showed results similar to and directly proportional to those obtained for ATR and ISP (Figure 3D), in which higher and constant values were obtained in seasons 1 (13253, 81 kg ha^{-1}) and 2 (11015.19 kg ha^{-1}), and in season 3, where the straw level was influenced, an increase in TAH was again observed with 5 Mg ha^{-1} of straw on the soil.

It should be seen that the worst results for the production variables (Figure 3) obtained in season 3 are caused by frosts responsible for anticipating the harvest at that time. Despite this and the small effect of straw on such variables, it is noteworthy that maintaining an intermediate amount of straw in the field, at season 3, increases ISP and TAH of the late variety in the experimental region. In this sense, Melo *et al*. (2020) observed that maintaining quantities of straw in the soil, between 8 and 13 Mg ha^{-1}, is sufficient to sustain the physical conditions of the soil for root growth and improve sugarcane yield; and according to the same authors, a better distribution of roots increases the volume of soil explored, which can increase the water and nutrient uptake by the plant.

CONCLUSIONS

- In sugarcane harvesting at the beginning of the crop (first season), after one year of evaluation, it was found, on the mean of straw levels, a reduction in density and an increase in total porosity up to 0.20 m deep, as well as an increase in macropores, in the 0.00-0.05 and 0.10-0.15 m layers, and RP reduction, in the 0.00-0.10 m layer.
- In mid-season harvest (second season), after one year of evaluation, there was an increase in PR for all remaining straw levels, with a reduction in soil density only in the 0.15-0.20 m layer, on the mean of straw levels or when 10 Mg ha^{-1} of straw was maintained in the soil
- In harvesting at the end of the season (third season), up to 0.20 m deep, there was a reduction in RP with the maintenance of 15 Mg ha^{-1} straw remaining on the soil; although, on the means of treatments, there were increases in RP up to 0.30 m depth, after one year of evaluation.
- Levels of straw did not influence stalk production in the beginning (first season) and middle (second season) harvest and in the end-of-season harvest (third season). Maximum stalk production was obtained with the maintenance of 5 Mg ha^{-1} of remaining straw.

AUTHORSHIP CONTRIBUTION STATEMENT

SILVA NETO, J. A.: Conceptualization, Data curation, Investigation, Validation, Writing – original draft; **ARCOVERDE, S. N. S.:** Formal Analysis, Software, Validation, Visualization, Writing – review & editing; **SOUZA, C. M. A.:** Methodology, Project administration, Supervision, Validation, Visualization; **SILVA, C. J.:** Methodology, Project administration, Supervision, Validation, Visualization.

DECLARATION OF INTERESTS

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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