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Effect of postharvest sugarcane straw amount and herbicides on *Digitaria* spp. control and green cane yield

Rosilaine Araldi de Castro[1], Sérgio Gustavo Quassi de Castro[2], Lauren Maine Santos Menandro[2], Marcos Antônio Kuva[3] and João Luis Nunes Carvalho[2]

[1]Researcher, AgroQuatro-S Experimentation and Applied Agronomic Consultancy, São Paulo, Brazil; [2]Researcher, Brazilian Biorenewables National Laboratory (LNBR), Brazilian Center for Research in Energy and Materials (CNPEM), São Paulo, Brazil and [3]Researcher, Herbae-Agronomic Consultancy and Projects Ltd., São Paulo, Brazil

Research Article

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Corresponding author:
Rosilaine Araldi de Castro;
Email: rosilainearaldi@hotmail.com

Abstract

New agronomic practices are emerging in the green cane system to utilize sugarcane (*Saccharum officinarum* L.) straw for energy cogeneration, which necessitates its removal from the soil surface. This study has three main objectives: (1) evaluate the population dynamics and composition of Jamaican crabgrass (*Digitaria horizontalis* Willd.) and large crabgrass [*Digitaria sanguinalis* (L.) Scop.] under different sugarcane straw amounts, with and without herbicide treatment; (2) assess the development of sugarcane under different straw amounts; and (3) determine the amount of sugarcane straw that should be kept on the soil surface after harvest to ensure that it does not compromise the chemical control for *Digitaria* spp. in ratoon cane in a green cane system. We conducted this research at two experimental sites, one at the beginning and the other during the middle of the harvest season, over a span of 2 yr. Our primary treatments consisted of different amounts of sugarcane straw after harvest on the soil surface (0, 5, 10, and 15 Mg ha^{-1}), while secondary treatments included the herbicide application (sulfentrazone + tebuthiuron for the beginning of harvest season and isoxaflutole + tebuthiuron for the middle of harvest season). The *Digitaria* spp. exhibited higher density (four times more) and dry matter (two times more) in scenarios with a lower sugarcane straw amount (5 Mg ha^{-1}) on the soil surface and no herbicide application. However, a higher straw amount (15 Mg ha^{-1}) contributed to reduced *Digitaria* spp. infestation and to improved sugarcane yield. According to this research, it is essential to maintain at least 10 Mg ha^{-1} of sugarcane straw on the soil surface and remove only 5 Mg ha^{-1} for energy cogeneration.

Introduction

Sugarcane (*Saccharum officinarum* L.) is a crop of significant global importance (Galon et al. 2022; Queiroz et al. 2022), serving as a raw material for sugar production and bioethanol and offering great potential for bioenergy generation. Sugarcane cultivation covers approximately 9 million ha in Brazil, where the largest cultivation area is in the southcentral region (85%), with emphasis on the state of São Paulo (4.4 million ha) (CONAB 2023). In Brazil, the majority of sugarcane production takes place through a conservation system known as green cane (Araldi de Castro et al. 2023). This system, characterized by the absence of preharvest burning, results in substantial amounts of straw on the soil surface, ranging from 10 to 20 Mg ha^{-1} (Silva et al. 2019; Tropaldi et al. 2021).

Sugarcane yields can be affected by various factors, including soil conditions, cultivated variety planted, pest and disease incidence, weed competition, and plant phytotoxicity due to herbicide application (Reis et al. 2019; Victoria-Filho and Christoffoleti 2004). Weed interference plays a critical role in this cropping system (Martins et al. 2022; Mossin et al. 2019). Failure to control weeds can lead to significant reduction in sugarcane yield of up to 81% (Kuva et al. 2001). This reduction can be attributed to direct factors such as competition for nutrients, light, water, and space, as well as allelopathy and parasitism, and indirect factors such as creeping plants that overload harvesters (Galon et al. 2022; Negrisoli et al. 2023; Schedenffeldt et al. 2022). Given the multiple crop cycles of sugarcane in Brazilian fields, typically five or six harvest seasons, inadequate weed control in the current cycle may lead to an increase in weed seed presence in the subsequent cycle (Araldi de Castro et al. 2023). This can result in less effective weed management in the field, as well as lower industrial quality of the raw material, impacting harvesting and transportation operations (Martins et al. 2022).

Chemical weed control using pre- and postemergence herbicides is the main method due to its cost-effectiveness and viability, especially in large sugarcane fields that require rapid and efficient weed management (Galon et al. 2022; Martins et al. 2022; Reis et al. 2019). Additionally, the use of herbicide in tank mixtures is a valuable strategy for reducing weed control costs, as it broadens the spectrum of control and minimizes the number of applications. In the southcentral region from Brazil, highlighting São Paulo state, the sugarcane harvesting seasons are divided into: beginning season (March to May), middle season (June to August), and late season (September to November). It is important to have adequate herbicide options in tank mixtures for each season on ratoon cane (Reis et al. 2019).

Digitaria spp. are among the grass weeds found in Brazilian sugarcane fields (Schedenffeldt et al. 2022; Toledo et al. 2017). *Digitaria* spp. are considered to be among the most aggressive weeds due to their highly competitive potential and dispersal capacity. These species are commonly encountered in sugarcane fields and can cause significant damage when present in high densities (Schedenffeldt et al. 2022). The prevalent species in Brazilian sugarcane systems are Jamaican crabgrass (*Digitaria horizontalis* Willd.), naked crabgrass (*Digitaria nuda* Schumach.), large crabgrass [*Digitaria sanguinalis* (L.) Scop.], and southern crabgrass [*Digitaria ciliaris* (Retz.) Koeler] (Tropaldi et al. 2015). The introduction of green cane has altered weed dynamics in ratoon cane (Araldi de Castro et al. 2023). Sugarcane straw has been important in suppressing the emergence of many monocotyledons, such as *Digitaria* spp. (Tofoli et al. 2009). Sugarcane straw can influence weed emergence through three distinct processes: physical, biological, and chemical (straw allelopathy), with or without interactions occurring between them (Silva Junior et al. 2016). The higher amount of sugarcane straw cover (near 15 Mg ha^{-1}) physically impacts the emergence of small-seeded species on the soil surface, affecting seedling development and survival and rendering seedlings more susceptible to mechanical damage (Correia and Durigan 2004; Silva Junior et al. 2016). Excellent control of *D. nuda* and *D. horizontalis* through sugarcane straw left on the soil surface has been reported, with the adequate straw amount to guarantee the reduction or absence of grass weeds in ratoon cane ranging from 6 Mg ha^{-1} to 12 Mg ha^{-1} (Correia and Durigan 2004; Hoshino et al. 2017; Martins et al. 1999; Silva Junior et al. 2016; Yamauti et al. 2011). These data are crucial for determining the appropriate amount of straw to leave on the soil postharvest for weed control, especially given that straw is increasingly in demand for alternative sources of energy generation (Hoshino et al. 2017). However, changes in the agricultural environment resulting from straw deposition on the soil surface, due to mechanical sugarcane harvesting and subsequent removal for energy generation, can impact weed dynamics on ratoon cane postharvest (Carvalho et al. 2017; Silva Junior et al. 2016). Approximately 20% to 30% of sugarcane straw has been indicated to be removed on the field for a sustainable way related with alternative clean energy (Carvalho et al. 2019).

Agriculture is a dynamic field, characterized by constant changes in the sugarcane production system. Various scenarios have been explored concerning weed control in green cane systems. We hypothesize that it is possible to strike a balance by retaining a significant portion of sugarcane straw in the field to effectively control *Digitaria* spp. while utilizing the remaining straw for energy generation at the mill. This study has three main objectives: (1) evaluate the population dynamics and composition of *Digitaria* spp. under different sugarcane straw amounts, with and without herbicide treatment; (2) assess the development of sugarcane under different straw amounts; and (3) determine the amount of sugarcane straw that should be kept on the soil surface after harvest, to ensure that it does not compromise the chemical control for *Digitaria* spp. in ratoon cane in a green cane system.

Materials and Methods

The experiments were carried out in Quatá, São Paulo, Brazil, on farms owned by the Quatá Mill (Zilor Company). Two experimental sites were selected to coincide with different stages of the sugarcane harvest season: the beginning and the middle. These areas were selected for a 2-yr research study (Year 1: first ratoon cycle; Year 2: second ratoon cycle).

Descriptions of the Sites

Beginning of the Harvest Season

This experiment was conducted at Santo Antonio farm (22°20′84″S, 50°66′62″W). The study (ratoon cane) was carried out during two sugarcane crop cycles: 2016 to 2017 (first ratoon) and 2017 to 2018 (second ratoon). Before the treatments were set up, soil was collected from the experimental site for chemical and physical characterization, according to the methodology described by Raij et al. (2001). The soil pH was determined in a 0.01 M $CaCl_2$ solution, and soil organic matter was determined using dichromate oxidation. Sulfur was extracted using calcium phosphate (0.01 M); and phosphorus, potassium, calcium, and magnesium were extracted following the resin method (1 M $NaHCO_3$ at pH 8.5). H + aluminum was determined using the buffer Shoemaker-McLean-Pratt (SMP) method, and aluminum was determined with KCl extraction following analysis in atomic absorption spectrometry or spectrophotometry (Raij et al. 2001). The soil was classified as Arenic Kandiudults (Soil Survey Staff 2014), being that the soil texture was sandy loamy, having the following physical attributes: 86% sand, 7% silt, and 7% clay. The chemical attributes measured were as follows: pH of 6.1 ($CaCl_2$); 1.02% soil organic matter; 62 mg P dm^{-3}; K, Ca, Mg, H + Al, and CEC of 1.2, 31, 12, 13, and 57.3 mmolc dm^{-3}, respectively; and base saturation of 21.

The sugarcane variety cultivated in this field was 'Coopersucar/IAA SP83 2847', known for its good adaptability to sandy soils similar to those encountered in this study and suggested for harvesting at the beginning of crop season. Sugarcane was planted with double spacing (0.9 by 1.6 m), and the first harvest was performed in June 2016, preceding the installation of the experiment by 15 d.

In Year 1, herbicide treatments were applied in June 2016 in preemergence conditions under the following specific weather conditions monitored during application: 27.3 C temperature, 43% air humidity, and 2.2 km h^{-1} wind speed. In Year 2, the application took place in July 2017, with weather conditions consisting of 23 C temperature, 45% air humidity, and 1.5 km h^{-1} wind speed, also 15 d after harvest. The same combination of herbicides and doses used in the previous year of the experiment was applied: sulfentrazone + tebuthiuron (600 + 600 g ai ha^{-1}). That treatment was applied in the same plot when the experiment was repeated in the second year on the subsequent ratoon crop.

Middle of the Harvest Season

This experiment was conducted at Santana farm (22°22′88″S, 50°84′8″W). The study focusing on ratoon cane was carried out during the 2016 to 2017 (first ratoon cycle) and 2017 to 2018 (second ratoon cycle). The sandy soil was classified as Arenic Kandiudults (Soil Survey Staff 2014). The base saturation was 54%, and the soil composition was 80% sand, 4% silt, and 16% clay. The

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chemical attributes measured included: pH of 4.9 ($CaCl_2$); 0.7% soil organic matter; 4 mg P dm^{-3}; and K, Ca, Mg, H + Al, and CEC of 1.1, 15, 5, 18, and 21.1 mmolc dm^{-3}, respectively.

The sugarcane variety chosen for this area was 'Ridesa RB92 579', known for its good adaptability to sandy soils, as observed in this study conducted in this area for the middle of the harvest season. Sugarcane was planted with double spacing, and the first harvest was conducted in August 2016, and 15 d later was installed the experiment. In Year 1, herbicide treatments were applied in August 2016, under the following weather conditions: 29.6 C temperature, 32% air humidity, and 0.3 km h^{-1} wind speed. In Year 2, the application was carried out in July 2017 (15 d after the sugarcane harvest) under weather conditions of 22 C temperature, 39% air humidity, and 1.3 km h^{-1} wind speed. For this middle of harvest season, the same combination of herbicides and doses of isoxaflutole + tebuthiuron (90 + 900 g ai ha^{-1}) were used as in the previous year of the experiment as well as in the second year on the subsequent ratoon crop on the same experimental plot.

Experimental Design and Herbicide Treatments

The experimental design employed for both years was a randomized block design with a split-plot arrangement with four replications. The main plot treatments involved different amounts of aboveground straw (on a dry basis) placed on the soil surface: 0 Mg ha^{-1} (total removal), 5 Mg ha^{-1} (partial removal), 10 Mg ha^{-1} (partial removal), and 15 Mg ha^{-1} (no removal). The split-plot treatments consisted of: (1) herbicide application and (2) no herbicide application (untreated control). Each plot consisted of 6 sugarcane twin rows with interrow spacing of 1.6 m, each measuring 20 m in length. Each subplot contained 6 rows of sugarcane with interrow spacing of 1.6 m, each measuring 10 m in length. The straw amounts in each plot were manually adjusted after field harvest, following an assessment of humidity percentage to facilitate dry-basis calculations.

The herbicide was applied as a preemergence treatment. The specific herbicides used and their respective doses were determined in accordance with the plan of the mill's agronomic team: sulfentrazone + tebuthiuron (600 + 600 g ha^{-1}) for the beginning of the harvest season, and isoxaflutole + tebuthiuron (90 + 900 g ha^{-1}) for the harvest midseason. The herbicides were applied using a pressurized backpack sprayer (CO_2) equipped with a swath width of 3 m with six AI110.02 (TeeJet®, Teejet® Technologies, Glendale Heights, IL, USA) nozzle tips spaced 0.5 m apart at 250 to 280 kPa at a walking speed of 3.6 km h^{-1}.

Data Assessment

The parameters measured included weed composition, assessed using both density and dry matter, the percentage of weed control, phytotoxicity percentage, and sugarcane yield. Evaluations of the herbicide treatments were conducted at 30, 60, 90, 120, and 150 DAA.

The weed community's composition was evaluated by assessing emerging flora using sampling squares with dimensions of 0.5 by 0.5 m, randomly placed eight times within each subplot. Weeds were identified by morphological traits at the genus and species level and quantified through counting to determine the mean density; the main weeds found were *D. horizontalis* and *D. sanguinalis*. The collected weeds were placed in paper bags and then subjected to drying in an oven with forced aeration at a constant temperature of 75 C until weight stabilization was achieved. Subsequently, the dry biomass was determined using a precision balance, following the method outlined by Kuva et al. (2008b). Weed control (specifically *Digitaria* spp.) was assessed on a scale ranging from 0% to 100%, where 0% indicated the absence of weed control and 100% indicated the complete eradication of plants due to the herbicide's effects (Gazziero 1995). These control ratings were compared based on an untreated control that was maintained without herbicides during the preemergence phase throughout the experimental period. Other weeds were observed in the experimental plots: guineagrass [*Urochloa maxima* (Jacq.) R. Webster; syn.: *Panicum maximum* Jacq.], ilima (*Sida cordifolia* L.), common purslane (*Portulaca oleracea* L.), and littlebell (*Ipomoea triloba* L.). Simultaneously, any potential damage to the sugarcane crop was evaluated by determining the phytotoxicity percentage and assigning percentage-based ratings in comparison to untreated control plants (Gazziero 1995). Before the harvest, biometric evaluations were conducted in each plot to characterize sugarcane biomass production, specifically, stalk biomass production (in Mg ha^{-1}) was quantified in three rows measuring 2 m in length, located in the central area of each subplot.

Throughout the experimental period, weather conditions (e.g., rainfall and temperature) were monitored using an automatic weather station (Vantage Pro II, Decagon Devices, CA, USA). installed closer to the experimental areas (5 km). Using these weather parameters, the water balance (as shown in Figure 1) was calculated according the methodology described by Thornthwaite and Mather (1955).

Data Analysis

Statistical analysis was carried out on data from each harvest time and year evaluated was done, with the main variable being the sugarcane straw amount maintenance on the soil surface, and the second variable being the herbicide application. All the data sets were submitted to ANOVA (*F*-Test) at a 5% significance level. Following the principles of data normality, some parameters were transformed into square root ($x + 1$), being that, the means of the variables were compared using Tukey's test ($P < 0.1$). Statistical analyses were performed using the software AgroEstat v. 1.1 (Barbosa and Maldonado Junior 2015).

Results and Discussion

Weather Conditions

The first experimental year was wetter compared with the second year (season precipitation of 2,254 vs. 1,346 mm) such that the winter in Year 2 was more prolonged and had greater amplitude when compared with Year 1. Furthermore, the distribution of rainfall was more uniform in Year 1, providing better conditions for plant growth and development (Figure 1).

Beginning of the Harvest Season

Digitaria horizontalis *Density*

During the first year of evaluation, sulfentrazone and tebuthiuron showed great control of *D. horizontalis* at 90 DAA without weed presence, subsequently at 120 and 150 DAA plant density of 0.03 and 0.06 plants m^{-2} were recorded, respectively. At 120 and 150 DAA for herbicide treatment, there were no significant differences in weed density (varying from 0 to 0.12 plants m^{-2}) among the different straw quantities (0, 5, 10, and 15 Mg ha^{-1}) (Table 1). However, *D. horizontalis* presence was observed in the untreated control. The highest density occurred without any straw

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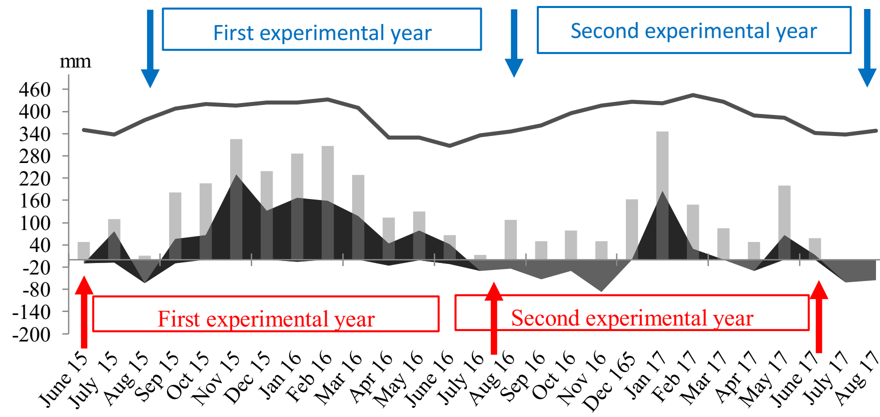

Figure 1. The water balance calculated during the experimental season for Year 1 and Year 2 for both beginning (red arrows) and middle of the harvest season (blue arrows) according to the methodology described by Thornthwaite and Mather (1955).

cover, followed by 5 Mg ha^{-1}, while the lowest densities were found at 10 and 15 Mg ha^{-1} at 120 and 150 DAA (Table 1). The monocotyledonous (Poaceae) weeds are important, with widespread occurrence in sugarcane growing areas (Kuva et al. 2008a; Reis et al. 2019). Major grass species competitors of sugarcane include *Digitaria* spp., *Brachiaria* spp., and *U. maxima* (Martins et al. 1999; Monquero et al. 2008).

Moving on to Year 2, an interaction between sugarcane straw amount and herbicide application was observed. Throughout the three evaluation periods (90, 120, and 150 DAA), the herbicide application consistently demonstrated lower *D. horizontalis* densities compared with the untreated control, with 33, 20, and 4 times more weeds in the untreated control for each respective period (Table 1). The smaller difference at 150 DAA was expected due to the gradual decrease in herbicide residues in the soil. Regarding differences in straw quantities, higher *D. horizontalis* densities (14 plants m^{-2} and 7 plants m^{-2}) were observed with the smaller straw amounts (0 and 5 Mg ha^{-1}). When comparing the average densities of the smaller straw amounts (0 and 5 Mg ha^{-1}) with the larger ones (10 and 15 Mg ha^{-1}) at 90, 120, and 150 DAA, we found 6, 2.5, and 2 times more *D. horizontalis* in the smaller straw layers. This highlights the significance of the physical presence of straw layers in inhibiting the germination and emergence of small-seeded weeds like *Digitaria* spp. (Table 1).

Weeds are usually more competitive than sugarcane crop. Schedenffeldt et al. (2022) concluded that the highest *Digitaria* spp. densities (80 plants m^{-1}) decreased the initial growth of sugarcane. Giraldeli et al. (2018) observed that 84 d of coexistence between *Digitaria* spp. plants and sugarcane seedlings coincided with the critical period for interference prevention. For our conditions, over an evaluated period of 150 d after planting, there was a 30% reduction in sugarcane yield when the density of *D. horizontalis* ranged from 35 to 69 plants m^{-1}.

Digitaria horizontalis *Dry Matter*

At 150 DAA, *D. horizontalis* was exclusively detected during the first year of evaluation in the untreated control. The highest amount was observed in the 0 Mg ha^{-1} layer (40 g m^{-2}), followed by the 5 Mg ha^{-1} layer (18 g m^{-2}). Interestingly, there was no significant difference between the dry matter in the larger layers of straw, namely 10 Mg ha^{-1} (9 g m^{-2}) and 15 Mg ha^{-1} (10 g m^{-2}), as shown in Table 2.

Even in this interesting scenario of reduction in *D. horizontalis* due to the presence of sugarcane straw (10 and 15 Mg ha^{-1}), herbicide applied to the straw layer is necessary and highly recommended. During the second year of evaluation, *D. horizontalis* was also present in the herbicide treatment, but the difference in dry matter was five times greater in the absence of herbicides compared with the chemical treatment. In other words, the use of sulfentrazone + tebuthiuron in both years had a significantly positive impact. The herbicides recommended for the control of *D. horizontalis* with more than 95% preemergence control are isoxaflutole, amicarbazone, metribuzin, oxyfluorfen, sulfentrazone, tebuthiuron, and trifluralin (Negrisoli et al. 2011; Takano et al. 2018). Tebuthiuron is a residual herbicide widely used in preemergence applications in green cane production to control the main annual species (Negrisoli et al. 2007; Tofoli et al. 2009). Moreover, there were no differences in the dry matter of *D. horizontalis* among the various straw amounts (0, 5, 10, and 15 Mg ha^{-1}) for Year 2.

Digitaria horizontalis *Control*

Similar values for *D. horizontalis* control percentage were observed in assessments conducted at 120 and 150 DAA. In the first year, the control percentage for *D. horizontalis* was 98% at 150 DAA. In the second year of evaluation, this control decreased to 92%, with the lower control in the second year attributed to higher weed density in the area, indicating a high infestation pressure (Table 3) and differing precipitation conditions (Figure 1). The chemical control of weeds in sugarcane is more effective when carried out during rainy seasons compared with drier seasons (Correia and Kronka 2010; Oliveira et al. 2020), because soil moisture and intense weed metabolism favor the absorption of most of the applied herbicides (Azania et al. 2009). However, due to the extensive harvesting period of sugarcane (from May to November —beginning, middle, and end of the harvest season) and the need to control weeds at the beginning of the sugarcane growth period, applications in the dry season are also fundamental for maintaining sugarcane yield (Takano et al. 2018).

The control percentage remained consistent, regardless of the presence or absence of straw. This suggests that the herbicides applied effectively passed through the straw and reached the soil, thus acting on the seedlings of *Digitaria* spp.

Table 1. Density results for *Digitaria horizontalis* in Year 1 and Year 2, assessed at 60, 90, 120, and 150 d after application (DAA), with and without the presence of the herbicides (sulfentrazone + tebuthiuron) across different amounts of straw at the beginning of the harvest season[a]

	Year 1[b]											
	60 DAA			90 DAA			120 DAA			150 DAA		
Straw	H	UC	A	H	UC	A	H	UC	A	H	UC	A
Mg ha^{-1}	plants m^{-2}											
0	0.00	0.00	0.00A	0.00Ab	1.60Aa	0.80	0.03Ab	3.31Aa	1.67	0.12Ab	3.06Aa	1.60
5	0.00	0.00	0.00A	0.00Aa	0.06Ba	0.03	0.03Ab	1.43Ba	0.73	0.12Ab	2.00Ba	1.06
10	0.00	0.00	0.00A	0.00Aa	0.00Ba	0.00	0.00Aa	0.09Ca	0.04	0.00Aa	0.37Ca	0.18
15	0.00	0.00	0.00A	0.00Aa	0.00Ba	0.00	0.06Aa	0.60BCa	0.33	0.03Ab	1.12Ca	0.58
Average	0.00a	0.00a		0.00	0.41		0.03	1.36		0.07	1.64	
F straw		—			12.93**			28.14**			24.22**	
F treatment		—			14.71**			98.59**			161.27**	
F s*t		—			12.93			27.85**			19.72**	
CV		—			11			54			41	
	Year 2[b]											
	60 DAA			90 DAA			120 DAA			150 DAA		
Straw	H	UC	A	H	UC	A	H	UC	A	H	UC	A
Mg ha^{-1}	plants m^{-2}											
0	0.00	0.00	0.00	1.25Ab	44.75Aa	23.00	1.13Ab	37.13Aa	19.13	5.88	23.25	14.56A
5	0.00	0.00	0.00	0.88Ab	19.50Ba	10.19	1.50Ab	24.63ABa	13.06	6.38	21.75	14.06A
10	0.00	0.00	0.00	0.13Aa	3.75Ca	1.94	1.13Aa	11.88Ba	6.50	3.13	10.88	7.00B
15	0.00	0.00	0.00	0.00Aa	7.00BCa	3.50	0.38Aa	11.50Ba	5.94	3.13	10.63	6.88B
Average	0.00	0.00		0.56	18.75		1.03	21.28		4.63b	16.63a	
F straw		—			44.31**			53.60**			144.72**	
F treatment		—			12.28**			5.36**			6.14**	
F s*t		—			10.88**			4.97*			2.22ns	
CV		—			80			68			46	

[a]H, herbicide; UC, untreated control; A, average; s*t, straw*treatment; CV, coefficient of variation.
[b]Means followed by the same uppercase letters in columns and lowercase letters in rows do not differ from each other by Tukey's test at 5% probability level. ** = significant at 1% by the *F*-test; * = significant at 5% by the *F*-test; ns = not significant.

Table 2. The dry matter results for *Digitaria horizontalis* at 150 d after application (DAA) for the assessed treatments are presented in relation to straw amounts along with the absence or presence of chemical weed control (sulfentrazone + tebuthiuron) at the beginning of the harvest season[a]

	Year 1[b]			Year 2[b]		
Straw	Herbicide	Untreated control	Average	Herbicide	Untreated control	Average
Mg ha^{-1}	g m^{-2}					
0	0Ab	40Aa	20	8.6	68	38A
5	0Ab	18ABa	9	21	140	81A
10	0Ab	9Ba	4	9	93	51A
15	0Ab	10Ba	5	5	65	35A
Average	0	19		11b	92a	
F straw		5.67**			2.23ns	
F treatment		88.55**			61.69**	
F s*t		5.67**			1.00ns	
CV		27			36	

[a]s*t, straw*treatment; CV.
[b]Means followed by the same uppercase letters in columns and lowercase letters in rows do not differ from each other by Tukey's test at 5% probability level.** = significant at 1% by the *F*-test; ns = not significant.

Sugarcane Phytotoxicity

In the evaluation of sugarcane phytotoxicity caused by the use of herbicide mixture, phytotoxicity was observed only during the first year. About 12% phytotoxicity was recorded up to 90 DAA, which then decreased to 3% (120 and 150 DAA). Notably, at 60 and 90 DAA, lower phytotoxicity levels (7% and 9%, respectively) were observed in areas with 5 Mg ha^{-1} of straw (Table 4). However, these values did not correlate with any significant changes in the final yield. Regarding application of the herbicide tebuthiuron to sugarcane, Azania et al. (2001) concluded that phytotoxicity was only observed in the initial phase of the crop, with complete recovery occurring 100 d after treatment. This recovery did not compromise sugarcane yield or the quality of the raw material. In fact, during the beginning of the harvest season at 90 DAA, the phytotoxicity observed in the initial assessments (up to 15%) had already been fully resolved. Sugarcane can tolerate damage comprising up to 27% of the leaf area without yield being impacted, and such injuries may be attributed to a cultivar's poor tolerance or improper herbicide use (Velini 1993).

Fagliari et al. (2008) and Toledo et al. (2017) reported that preemergence herbicide applications were generally selective for

Table 3. Percentage results for control of *Digitaria horizontalis* at 150 d after application (DAA) were assessed for various treatments. These treatments were based on different straw amounts and absence or presence of chemical weed control (sulfentrazone + tebuthiuron) in both Year 1 and Year 2, specifically at the beginning of the harvest season[a]

	150 DAA[b]					
	Year 1			Year 2		
Straw	Herbicide	Untreated control	Average	Herbicide	Untreated control	Average
Mg ha^{-1}	%					
0	99	0	49	92	0	46
5	98	0	49	92	0	46
10	100	0	50	94	0	47
15	98	0	49	91	0	46
Average	99a	0b		92a	0b	
F straw	1.11ns			0.80ns		
F treatment	72,584.2**			10,952.00**		
F s*t	1.11ns			0.80ns		
CV	2			4		

[a]s*t, straw*treatment; CV, coefficient of variation.
[b]Means followed by the same uppercase letters in columns and lowercase letters in rows do not differ from each other by Tukey's test at 5% probability level.** = significant at 1% by the *F*-test; ns = not significant.

Table 4. The percentage of sugarcane phytotoxicity was assessed at 30, 60, 90, 120, and 150 d after application (DAA) of sulfentrazone + tebuthiuron using different amounts of sugarcane straw during Year 1 at the beginning of the harvest season[a]

Straw	30 DAA	60 DAA	90 DAA	120 DAA	150 DAA
Mg ha^{-1}	%				
0	11a	15a	14a	4a	3a
5	9a	7b	9b	2a	3a
10	13a	14a	12a	3a	3a
15	14a	12a	14a	3a	4a
Average	12	12	12	3	3
F straw	2.22ns	6.84**	3.24**	0.68ns	1.45ns
CV[b]	35	29	31	24	33

[a]Means followed by the same uppercase letters in columns and lowercase letters in rows do not differ from each other by Tukey's test at 5% probability level. ** = significant at 1% by the *F*-test; ; ns = not significant.
[b]CV, coefficient of variation.

sugarcane. A factor favoring sugarcane selectivity is that, in general, herbicides are absorbed less by the crop compared with weeds. Araldi et al. (2011) found that weed plants typically consume about 2.5 times more water than sugarcane plants. Consequently, because sugarcane absorbs less herbicide due to its lower water intake, such selectivity is often maintained. It should be noted that the scientific studies in the literature vary as to factors such as application timing, sugarcane variety, soil type, and field treatment design.

Sugarcane Yield

Throughout the evaluations conducted in both Year 1 and Year 2, there were no significant differences in yield observed at the beginning of the harvest, irrespective of chemical control (Table 5). Herbicide selectivity for sugarcane cultivation has posed challenges for producers due to the diverse cultivation systems employed in Brazil (Franchini et al. 2020). In their study, Franchini et al. (2020) evaluated herbicide selectivity when applied pre- and postemergence in conventional systems with burning straw and in green cane systems. Among the 26 treatments assessed with preemergence applications, only 7 significantly reduced sugarcane yields. Additionally, the presence of different amounts of straw on the soil surface did not affect yield.

Middle of the Harvest Season

Digitaria sanguinalis *Density*

In the first year of the experiment, an interaction between the data revealed an overall low infestation of *D. sanguinalis*. There was no significant difference in weed density between the herbicide treatment and the untreated control (60 DAA). However, at 90 and 120 DAA, differences in weed density were observed among the different levels of straw covering the soil. The layers with 0 and 5 Mg ha^{-1} of straw had the highest weed density, while the larger straw layers showed almost no presence of *D. sanguinalis* (Table 6). In the second year of evaluation, the highest weed density continued to be in the smallest straw layers (0 and 5 Mg ha^{-1}).

Correia and Durigan (2004) verified that only higher amounts of sugarcane straw (i.e., 10 and 15 Mg ha^{-1}) resulted in a profound reduction of *D. horizontalis* weed infestation. In our study, the presence of sugarcane straw reduced the density of *D. sanguinalis* both at the beginning and middle of the harvest season in the two evaluation years, especially for larger amounts of straw maintained in the soil after harvest (10 and 15 Mg ha^{-1}). At 120 and 150 DAA, the herbicide treatment demonstrated lower infestation of *D. sanguinalis* compared with the untreated control, with differences of approximately 50% and 20%, respectively (Table 6).

Digitaria sanguinalis *Dry Matter*

When evaluating the dry matter of *D. sanguinalis* at 150 DAA, higher dry matter (60% or greater) was observed in the untreated control in the first year. However, in the second year, the highest dry matter of the weed was found in the absence of straw (0 Mg ha^{-1}), differing from the other straw amounts, which generally resulted in lower *D. sanguinalis* dry matter (Table 7). This difference amounted to a 60% increase in dry matter of *D. sanguinalis* in the absence of straw compared with its presence in Year 1 and a 30% increase in Year 2.

The majority of Brazilian sugarcane production is based on the green cane system. The presence of sugarcane straw residue on the soil surface by itself can reduce weed occurrence, which is a limiting factor for higher yields in sugarcane crop (Correia et al.

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Table 5. The sugarcane yield associated with different straw amounts as well as the with and without the presence of the herbicide (sulfentrazone + tebuthiuron) during 2 yr under evaluation (Year 1 and Year 2) at the beginning of the harvest season[a]

	Year 1[b]			Year 2[b]		
Straw	Herbicide	Untreated control	Average	Herbicide	Untreated control	Average
	Mg ha^{-1}					
0	40	48	44A	65	68	66A
5	50	44	47A	65	60	62A
10	45	49	47A	64	69	66A
15	45	43	44A	64	64	64A
Average	45a	46a		65a	65a	
F treatment		0.09ns			0.02ns	
F straw		0.36ns			0.46ns	
F t*s		1.23ns			0.49ns	
CV		18			13	

[a]s*t, straw*treatment; CV, coefficient of variation.
[b]Means followed by the same uppercase letters in columns and lowercase letters in rows do not differ from each other by Tukey's test at 5% probability level. ns = not significant.

Table 6. Density results for *Digitaria sanguinalis* in Year 1 and Year 2, assessed at 60, 90, 120, and 150 d after application (DAA), with and without the presence of the herbicide (isoxaflutole + tebuthiuron) across different straw amounts at the middle of the harvest season[a]

	Year 1[b]											
	60 DAA			90 DAA			120 DAA			150 DAA		
Straw	H	UC	A	H	UC	A	H	UC	A	H	UC	A
Mg ha^{-1}	plants m^{-2}											
0	0.00	0.00	0.00	1.09	1.09	1.09A	0.21	0.65	0.43A	0.25	0.12	0.18A
5	0.00	0.00	0.00	0.09	1.22	0.65AB	0.40	0.40	0.40A	0.34	0.06	0.20A
10	0.00	0.00	0.00	0.00	0.00	0.00B	0.03	0.03	0.03B	0.00	0.00	0.00A
15	0.00	0.00	0.00	0.00	0.03	0.01B	0.03	0.06	0.04B	0.06	0.03	0.04A
Average	0.00	0.00		0.29a	0.41a		0.17a	0.29a		0.16 a	0.05a	
F straw		—			4.04*			4.37*			3.01ns	
F treatment		—			0.82ns			0.89ns			3.22ns	
F s*t		—			0.75ns			0.83ns			1.08ns	
CV		—			24			12			7	
	Year 2[b]											
	60 DAA			90 DAA			120 DAA			150 DAA		
Straw	H	UC	A	H	UC	A	H	UC	A	H	UC	A
Mg ha^{-1}	plants m^{-2}											
0	0.00	0.00	0.00	49.38	63.75	56.56A	22.00	32.13	27.06A	61.00	68.88	64.94A
5	0.00	0.00	0.00	13.88	28.00	20.94B	7.38	20.50	13.94B	35.75	46.00	40.88B
10	0.00	0.00	0.00	7.88	9.50	8.69BC	3.75	7.50	5.63BC	17.25	27.38	22.31BC
15	0.00	0.00	0.00	0.00	1.00	0.50C	0.88	3.13	2.00C	9.50	11.00	10.25C
Average	0.00	0.00		17.78a	25.56a		8.50 b	15.81a		30.88b	38.31a	
F straw		—			27.75**			18.88*			19.48*	
F treatment		—			6.99ns			20.84*			11.63*	
F s*t		—			0.63ns			1.02ns			0.14ns	
CV		—			61			60			60	

[a]H, herbicide; UC, untreated control; A, average; s*t, straw*treatment; CV, coefficient of variation.
[b]Means followed by the same uppercase letters in columns and lowercase letters in rows do not differ from each other by Tukey's test at 5% probability level. ** = significant at 1% by the *F*-test; * = significant at 5% by the *F*-test; ns = not significant.

2006; Hoshino et al. 2017; Silva et al. 2009). The presence of sugarcane straw can influence the dormancy, germination, and mortality of weed seeds, leading to changes in the composition of weed communities. These changes are difficult to predict, because they depend on the thickness of the straw layer on the soil and the species of weed affected by soil cover (Carvalho et al. 2017; Correia and Durigan 2004). The adoption of sugarcane in the green cane system facilitates the control of some weeds with small seeds (Carvalho et al. 2017; Correia et al. 2006). Hoshino et al. (2017) found a linear decrease in weed density with an increase in sugarcane straw amount. Treatments between 15 and 20 Mg ha^{-1} of sugarcane straw showed the lowest area occupied by weeds. Toledo et al. (2009) concluded that maintaining an optimal quantity of straw (10 Mg ha^{-1}) can lead to more sustainable control of the main weeds of economic significance in the sugarcane crop. Hassuani et al. (2005) analyzed the results of an experimental network of 56 sugarcane harvests in São Paulo State and found that maintaining amounts of sugarcane straw equal to or higher than

Table 7. The dry matter results for *Digitaria sanguinalis* at 150 d after application (DAA) for the assessed treatments are presented in relation to straw amounts along with the absence or presence of chemical weed control (isoxaflutole + tebuthiuron) at the middle of the harvest season[a]

	Year 1[b]			Year 2[b]		
Straw	Herbicide	Untreated control	Average	Herbicide	Untreated control	Average
Mg ha^{-1}			g m^{-2}			
0	58	115	87A	90	384	237A
5	18	54	36B	60	352	206B
10	14	79	47B	57	212	135B
15	19	33	26B	52	251	151B
Average	27b	70a		68b	300a	
F straw		1.80ns			12.77*	
F treatment		56.08**			4.49*	
F s*t		0.86ns			2.22ns	
CV		33			30	

[a]s*t, straw*treatment; CV, coefficient of variation.
[b]Means followed by the same uppercase letters in columns and lowercase letters in rows do not differ from each other by Tukey's test at 5% probability level. ** = significant at 1% by the *F*-test; * = significant at 5% by the *F*-test; ns = not significant.

Table 8. Percentage results for control of *Digitaria sanguinalis* at 150 d after application (DAA) were assessed for various treatments based on different straw amounts and absence or presence of chemical weed control (isoxaflutole + tebuthiuron) in both Year 1 and Year 2, specifically at the middle of the harvest season[a]

	150 DAA[b]					
	Year 1			Year 2		
Straw	Herbicide	Untreated control	Average	Herbicide	Untreated control	Average
Mg ha^{-1}			%			
0	85	0	42	50Da	0Ab	25
5	85	0	42	70Ca	0Ab	35
10	85	0	42	77Ba	0Ab	39
15	90	0	42	98Aa	0Ab	49
Average	86a	0b		748a	0b	
F straw		1.24ns			82,045.00**	
F treatment		923.09*			406.00**	
F s*t		1.10ns			406.00**	
CV		2			12	

[a]s*t, straw*treatment; CV, coefficient of variation.
[b]Means followed by the same uppercase letters in columns and lowercase letters in rows do not differ from each other by Tukey's test at 5% probability level. ** = significant at 1% by the *F*-test; * = significant at 5% by the *F*-test; ns = not significant.

8 Mg ha^{-1} resulted in an average efficiency in weed control of 87%, while amounts lower than 8 Mg ha^{-1} reduced the average efficiency to 56%, as these straw amounts are not always uniformly distributed on the soil (Carvalho et al. 2017).

Digitaria sanguinalis Control

The percentage control achieved at 120 DAA in the middle of the harvest season (drier season) was similar to that observed at 150 DAA. In the first year, an average of 86% control was observed for the treatment (isoxaflutole + tebuthiuron) against *D. sanguinalis*, while in the second year, this control rate dropped to 74% in general. Recently, herbicide formulations have been reconfigured for adverse dry conditions, with improvements in their formulations and adjustments in herbicide doses. Sulfentrazone is regularly applied to sugarcane crop harvest residue for preemptive control of weedy species, especially during the dry season (Carbonari et al. 2016). According to Guimarães (1987), the characteristics that contribute to maintaining herbicide efficiency in the soil during periods of drought include low volatility, low photodegradability, high solubility, low adsorption of soil colloids, and degradation, especially by microorganisms.

In the second year, control varied as a function of different amounts of sugarcane straw. The best control was achieved with 15 Mg ha^{-1} (98%), while the lowest control was observed in the absence of straw (0 Mg ha^{-1}), resulting in 50% control of *D. sanguinalis*. The other layers had intermediate control rates of 77% (10 Mg ha^{-1}) and 70% (5 Mg ha^{-1}) (Table 8). This higher control resulted in greater yield. A number of weed scientists have studied the occurrence of weeds in sugarcane crops in relation to the amount of straw covering the soil (Carbonari et al. 2010; Hoshino et al. 2017). Silva Junior et al. (2016) conducted a study on the effects of different sugarcane straw amounts on the emergence of *D. nuda*, and found that increasing amounts of sugarcane straw reduced *D. nuda* seedling emergence. Consequently, it may no longer pose a problem in green cane areas (Klein and Felippe 1991).

Sugarcane Phytotoxicity

Phytotoxicity in the sugarcane crop was only observed at 30 DAA in the first year of assessment. This phytotoxicity disappeared in subsequent evaluations. The highest level of phytotoxicity was found under 15 Mg ha^{-1} of straw (14%), followed by 10 and 5 Mg ha^{-1} (11%). The lowest phytotoxicity occurred in the absence of straw (7%), as shown in Table 9. Straw likely retained the herbicide, causing slight phytotoxicity in the plants at the initial stage. However, this did not adversely affect the final yield in any way.

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Table 9. The percentage of sugarcane phytotoxicity was assessed at 30 and 60 d after application (DAA) of isoxaflutole + tebuthiuron herbicides, using different amounts of sugarcane straw during Year 1 at the middle of the harvest season[a]

Straw	30 DAA	60 DAA
Mg ha^{-1}	%	
0	7B	0
5	11AB	0
10	12AB	0
15	14A	0
Average	11	0
F straw	5.49**	—
CV[b]	21	—

[a]Means followed by the same uppercase letters in columns and lowercase letters in rows do not differ from each other by Tukey's test at 5% probability level. ** = significant at 1% by the *F*-test; ns = not significant.
[b]CV, coefficient of variation.

Table 10. The sugarcane yield associated with different straw amounts as well as the with and without the presence of the herbicide (isoxaflutole + tebuthiuron) during 2 yr under evaluation (Year 1 and Year 2) at the middle of the harvest season[a]

	Year 1[b]			Year 2[b]		
Straw	Herbicide	Untreated control	Average	Herbicide	Untreated control	Average
			Mg ha^{-1}			
0	77	73	75A	39	37	38B
5	73	73	73A	46	41	44AB
10	75	70	73A	52	49	50A
15	79	75	77A	48	50	49A
Average	76a	73a		46a	44a	
F treatment		1.47ns			9.68**	
F straw		0.42ns			2.21ns	
F t*s		0.09ns			0.51ns	
CV		11			8	

[a]s*t, straw*treatment; CV, coefficient of variation.
[b]Means followed by the same uppercase letters in columns and lowercase letters in rows do not differ from each other by Tukey's test at 5% probability level. ** = significant at 1% by the *F*-test; ns = not significant.

Green cane cultivation exhibited a higher frequency of nonselective treatments, especially when herbicides were used in tank mixtures. In green cane crops with straw present, the mass of roots in the surface layers of the soil (0 to 0.2 m) was greater compared with crops without straw (Aquino et al. 2015). This increased root mass could contribute to higher herbicide absorption in green cane systems, potentially leading to greater phytotoxicity in certain cases (Dias et al. 2017; Franchini et al. 2020). In our study, the greatest phytotoxicity was indeed observed in the presence of straw. In Year 1 in the middle of the harvest season, the highest phytotoxicity (15%) was recorded when the straw quantity was 15 Mg ha^{-1}.

According to Souza et al. (2009), the selectivity of herbicides in sugarcane cultivation can vary depending on factors, including climatic conditions. Sugarcane harvested at the beginning of the harvest season, during the wet season, tends to have more soil moisture compared with the middle of the harvest season, which is drier. Toledo et al. (2015) concluded that sulfentrazone, among other herbicides evaluated, when applied preemergence in sugarcane crops during the dry season, did not cause phytotoxicity in the initial stages of crop development. Similarly, herbicide in tank mixtures such as amicarbazone with isoxaflutole and tebuthiuron with isoxaflutole showed no phytotoxicity up to 120 DAA. In our research, phytotoxicity occurred for a shorter duration (only 30 d) during midseason compared with the beginning of the harvest season (90 d).

Some herbicides can reduce sugarcane yields without causing visually detectable effects, while others can cause severe injuries but still allow for full recovery of the sugarcane (Bunhola and Segato 2017). The phytotoxicities observed in the current study did not negatively impact the final sugarcane yield.

Sugarcane Yield

In the first year of evaluation, there was no significant difference in sugarcane yield when comparing the untreated control with the tank mixture of isoxaflutole + tebuthiuron. However, in the second year, yield varied based on straw amount. The highest yield was produced by 10 and 15 Mg ha^{-1} of straw (50 Mg ha^{-1}), while the layer with 5 Mg ha^{-1} of straw resulted in an intermediate yield (44 Mg ha^{-1}). The lowest yield was obtained in the absence of straw (38 Mg ha^{-1}) (Table 10).

The amount of sugarcane straw left on the soil after harvest in the green cane system can benefit the sugarcane crop by enhancing nutrient absorption, potentially increasing yield by up to 30% (Ball-Coelho et al. 1993, Hoshino et al. 2017). In the middle of the harvest season in Year 2, maintaining 10 or 15 Mg ha^{-1} of sugarcane straw on the soil surface led to a 32% increase in sugarcane yield. However, it is worth noting that other studies have shown conflicting results, suggesting that an excess of straw on the soil can harm plants and result in yield losses (Campos et al. 2008; Leavitt et al. 2011).

In summary, straw helped control *Digitaria* spp., promoted good herbicide dynamics, maintained soil moisture, and brought several benefits to the soil, resulting sometimes in higher sugarcane yield with 10 and 15 Mg ha^{-1} of straw covering the soil surface. To strike a balance regarding the optimal amount of sugarcane straw to retain on the soil, Aquino and Medina (2014) demonstrated that maintaining 50% or 75% of the straw may enhance sugarcane yields. This scientific insight is crucial for determining the appropriate amount to leave on the field, especially considering the growing demand for straw as an alternative energy source, such as for thermal or second-generation bioethanol production (Canilha et al. 2012; Soccol et al. 2010). Our paper aligns with the idea that it is advisable to retain the largest portion of sugarcane straw in the field after harvest, as it not only effectively controls *Digitaria* spp. but also maintains or improves sugarcane yields.

In conclusion, the weed under study, *Digitaria* spp., exhibited a higher density and dry matter when there was a lower amount of sugarcane straw present on the soil surface and no herbicides were applied in both sites at the beginning and middle of harvest season. Although a higher straw amount (15 Mg ha^{-1}) initially led to phytotoxicity in sugarcane plants, it did not affect sugarcane yield. On the contrary, this higher straw amount resulted in a higher yield for the second year in the middle of harvest season. According to this research, it is essential to maintain at least 10 Mg ha^{-1} of sugarcane straw on the soil surface and remove only 5 Mg ha^{-1} for energy cogeneration. Whenever possible, it is advisable to retain all straw in the field.

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