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Scientific Article

Tillage systems and straw levels: soil biological quality and sugarcane yield

Sistemas de preparo e níveis de palhiço: qualidade biológica do solo e produtividade da cana-de-açúcar

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ABSTRACT – Studies integrating factors influencing soil biological quality, soil macrofauna, and their relationships with sugarcane yield remain limited. The objective of this study was to evaluate soil biological quality, soil macrofauna, and sugarcane yield under different soil tillage systems and straw retention levels. The experiment was conducted in a clay-textured Typic Hapludox at an experimental area of the Brazilian Agricultural Research Corporation (Embrapa Agropecuária Oeste), in partnership with the São Fernando sugar mill, in Dourados, Mato Grosso do Sul, Brazil. A randomized block design with four replications was used in a split-plot arrangement, with plots comprising no-tillage and conventional tillage systems and subplots comprising straw retention levels (0%, 50%, and 100%). Microbial biomass and soil macrofauna were evaluated at four different sampling times. Accumulated stalk and sugar yields were determined at the end of the crop cycle. In both soil tillage systems, maintaining straw on the soil improved soil microbiological quality and soil macrofauna attributes, particularly under conventional tillage. Adoption of no-tillage combined with retention of 100% straw increased stalk and sugar yield over a single sugarcane crop cycle.

Keywords: Bioindicators. Soil microbial biomass. No-tillage system. Plant residues.

RESUMO - Estudos que integram fatores que influenciam a qualidade biológica do solo, a macrofauna edáfica e suas relações com a produtividade da cana-de-açúcar ainda são escassos. O objetivo deste estudo foi avaliar a qualidade biológica do solo, a macrofauna edáfica e a produtividade da cana-de-açúcar sob diferentes sistemas de preparo do solo e níveis de retenção de palha. O experimento foi conduzido em um Latossolo Vermelho distrófico típico de textura argilosa, em área experimental da Empresa Brasileira de Pesquisa Agropecuária (Embrapa Agropecuária Oeste), em parceria com a usina São Fernando, no município de Dourados, Mato Grosso do Sul, Brasil. Utilizou-se o delineamento em blocos ao acaso, com quatro repetições, em esquema de parcelas subdivididas, sendo as parcelas constituídas pelos sistemas de preparo do solo (plantio direto e preparo convencional) e as subparcelas pelos níveis de retenção de palha (0%, 50% e 100%). A biomassa microbiana e a macrofauna do solo foram avaliadas em quatro épocas de amostragem. As produtividades acumuladas de colmos e de açúcar foram determinadas ao final do ciclo da cultura. Em ambos os sistemas de preparo do solo, a manutenção da palha sobre a superfície do solo promoveu melhorias na qualidade microbiológica do solo e nos atributos da macrofauna edáfica, com efeitos mais pronunciados sob preparo convencional. A adoção do plantio direto associada à retenção de 100% da palha aumentou a produtividade de colmos e de açúcar ao longo de um ciclo de cultivo da cana-de-açúcar.

Palavras-chave: Bioindicadores. Biomassa microbiana do solo. Sistema plantio direto. Resíduos vegetais.

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INTRODUCTION

Sugarcane is one of the world's major crops, cultivated in more than 100 countries. Approximately 83% of global sugarcane production is concentrated in ten countries, with Brazil as the largest producer, accounting for approximately 37% (746 million Mg) of annual global production (ARCOVERDE et al., 2023). Sugarcane is a high-energy biomass crop, with sugar accumulated in the stalks, serving as raw material for ethanol and sugar production. In addition, the lignocellulosic residue generated after sugar extraction can be used for biofuel production or other bioproducts (AWE; REICHERT; FONTANELA, 2020).

Although the sugarcane industry currently uses straw extensively as a raw material for bioenergy production, retaining it in the field can improve soil chemical, physical, and biological properties; reduce thermal amplitude in surface soil layers; increase water infiltration rate; maintain soil moisture (SANTOS et al., 2022); control erosion; and decrease susceptibility to compaction (CASTIONI et al., 2019). Furthermore, the improved microclimate provided by straw cover on the soil (AWE; REICHERT; FONTANELA, 2020; SANTOS et al., 2022), combined with continuous carbon inputs, promotes long-term increases in soil organic matter content (BORDONAL et al., 2018; CHERUBIN et al., 2019), positively affecting soil biota, soil physical functioning and nutrient cycling (CHERUBIN et al., 2019). These changes influence soil conditions and sugarcane root growth, yield, quality, and longevity (MELO et al., 2020).

Experiments developing conservation-based soil management practices under diverse edaphoclimatic conditions are essential for sustainable sugarcane production, particularly in environments with soils subjected to physical or chemical limitations and periodic water deficits (ARCOVERDE et al., 2023; ARCOVERDE et al., 2025). In this context, no-tillage represents a viable alternative, and studies have shown promising results for sugarcane yield, partly due to the lower cultivation costs compared to conventional tillage systems (ARCOVERDE et al., 2023).

Intensive crops such as sugarcane, which involve extensive mechanization throughout the crop cycle, can alter soil conditions or reduce food availability for microorganisms due to straw removal from the soil surface, thereby intensifying adverse effects on microbial ecological interactions in the soil (MENANDRO et al., 2019). Vanolli et al. (2021) evaluated the sugarcane expansion into pasture areas and observed substantial losses in diversity and abundance of soil macrofauna, supporting the hypothesis that physical disturbances in cropping systems affect the activity of soil organisms. In contrast, straw retention in ratoon sugarcane enhances these attributes, indicating that soil organisms favor covered soils.

Systems with greater surface vegetation cover provide favorable environments for microorganisms through higher humidity, moderate temperature, and abundant nutrient resources (WANG et al., 2020). During the dry season, microbial biomass decreases substantially, but during the rainy season, soil moisture increases and surviving organisms use accumulated soil organic matter, resulting in higher microbial activity (GOMES et al., 2021). Furthermore, increases in microbial biomass carbon associated with straw decomposition may increase soil organic carbon content. According to Silva et al. (2015), lower metabolic quotient (qCO_2) values indicate greater agroecosystem stability, as higher efficiency of microbial biomass carbon in using ecosystem resources allows reduced losses through basal respiration ($C\text{-}CO_2$) and greater incorporation of carbon into microbial tissues, resulting in a lower qCO_2 (KOUDAHE; ALLEN; DJAMAN., 2022).

Experiments integrating the multiple factors influencing soil biological quality and their effects on sugarcane nutrition and yield remain limited, particular with long-term monitoring to enable optimal straw management. In Mato Grosso do Sul, Brazil, no prior experiment has adopted this approach integrating assessments of soil biological quality, soil macrofauna, and sugarcane yield under different soil management practices. The objective of this study was to evaluate soil biological quality, soil macrofauna, and sugarcane yield under different soil tillage systems and straw retention levels.

MATERIAL AND METHODS

Study site, soil, and climate

The experiment was conducted over a full sugarcane crop cycle, encompassing the first, second, third, fourth, and fifth ratoons (2014–2015 to 2018–2019). The soil was classified as a Typic Hapludox (Latossolo Vermelho Distroférrico típico) (SOIL SURVEY STAFF, 2022; SANTOS et al., 2025) with clay, silt, and sand contents of 722, 120, and 158 g kg^{-1} (0–0.10 m layer); 743, 104, and 153 g kg^{-1} (0.10–0.20 m layer); and 780, 79, and 141 g kg^{-1} (0.20–0.40 m layer), respectively. The experiment was located at an experimental area of the Brazilian Agricultural Research Corporation (Embrapa Agropecuária Oeste), in partnership with the São Fernando sugar mill, in Dourados, Mato Grosso do Sul, Brazil (22°25′86″S, 54°97′47″W; altitude 410 m) (Figure 1). The climate of the region is classified as Cwa, humid temperate with dry winter and hot summer, according to the Köppen–Geiger classification system.. Meteorological data from the Dourados station (Embrapa Climate Guide) recorded annual rainfall and mean air temperature of 1,707 mm and 23.3 °C (2015); 1,341 mm and 22.4 °C (2016); 996 mm and 23.4 °C (2017); 1,314 mm and 23.0 °C (2018); and 890 mm and 24.1 °C (2019) (Figure 2).

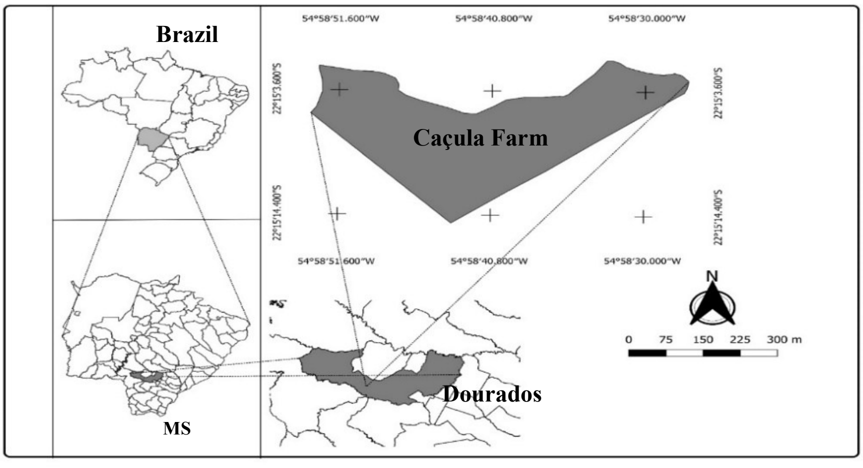


Figure 1. Geographic location of the experimental area.

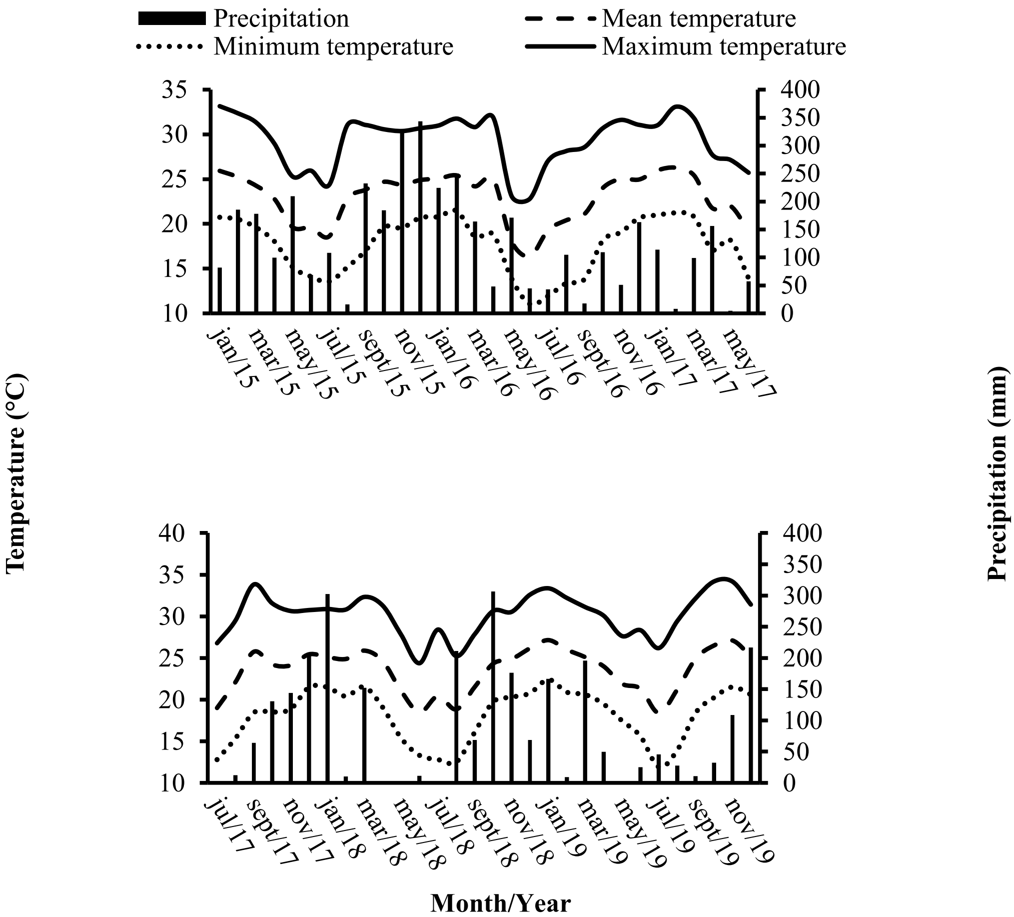


Figure 2. Monthly accumulated rainfall and mean air temperatures from 2015 to 2019. Source: Embrapa (2024).

Experimental design

A randomized block design with four replications was used in a split-plot arrangement, with plots comprising no-tillage and conventional tillage systems and subplots comprising straw retention levels: 0% (total straw removal), 50% (partial straw removal), and 100% (no straw removal). Each plot comprised six sugarcane rows 30 m in length, spaced 1.5 m apart, totaling an area of 270 m².

Area history, experiment setup, and conduction

The experimental area was cultivated with sugarcane in the last ratoon (2011–2012), whose regrowth was chemically desiccated by applying 6.0 L ha^{-1} of glyphosate and 1.8 L ha^{-1} of 2,4-D, with a spray volume of 150 L ha^{-1}. Agricultural gypsum (2.0 Mg ha^{-1}) and dolomitic limestone (4.0 Mg ha^{-1}) were surface-applied in no-tillage plots, whereas in conventional tillage plots, these amendments were incorporated together with residual straw through sequential plowing, subsoiling, intermediate harrowing, and leveling harrowing. The entire experimental area was planted with soybeans in the 2012–2013 growing season and, after harvest in March 2013, sugarcane cultivar RB966928 (recommended for medium-restriction environments) was planted mechanically in single rows spaced 1.5 m apart. At planting, 600 kg ha^{-1} of the 05–25–25 N–P–K formulation was applied to the furrow bottom throughout the experimental area. At 150 days after planting, ridge-breaker operations were performed and 130 kg ha^{-1} of N (as urea) was applied.

Thirty days after harvest of each ratoon cycle—first (2014–2015), second (2015–2016), third (2016–2017), fourth (2017–2018), and fifth (2018–2019)—120 kg ha^{-1} of K_2O (as potassium chloride) was broadcast manually on the soil surface, parallel to the planting row (on both sides), and 150 kg ha^{-1} of N (as urea) was distributed and incorporated using a ratoon scarifier without tines. After the third ratoon harvest in 2017, dolomitic limestone (4 Mg ha^{-1}) was applied to all plots in both tillage systems. Weed and pest control measures were implemented as required, following recommendations for sugarcane cultivation at São Fernando sugar mill.

After each sugarcane harvest, total straw mass for each treatment was quantified using a 0.5 m^2 metal frame (1.0 m × 0.50 m) randomly placed in the plot, with two replicates per plot. Straw collected from within the frame was oven-dried and weighed to determine total straw mass (Figure 3A). Straw retention levels were subsequently adjusted in the subplots 100% (no removal), 50% (partial removal), and 0% (total removal) and remaining fresh straw and residual straw were quantified. Remaining fresh straw consisted of material measured immediately after sugarcane harvesting following partial (50%) or total (0%) straw removal, whereas residual straw consisted of the undecomposed fraction quantified immediately before the subsequent harvest (Figure 3B).

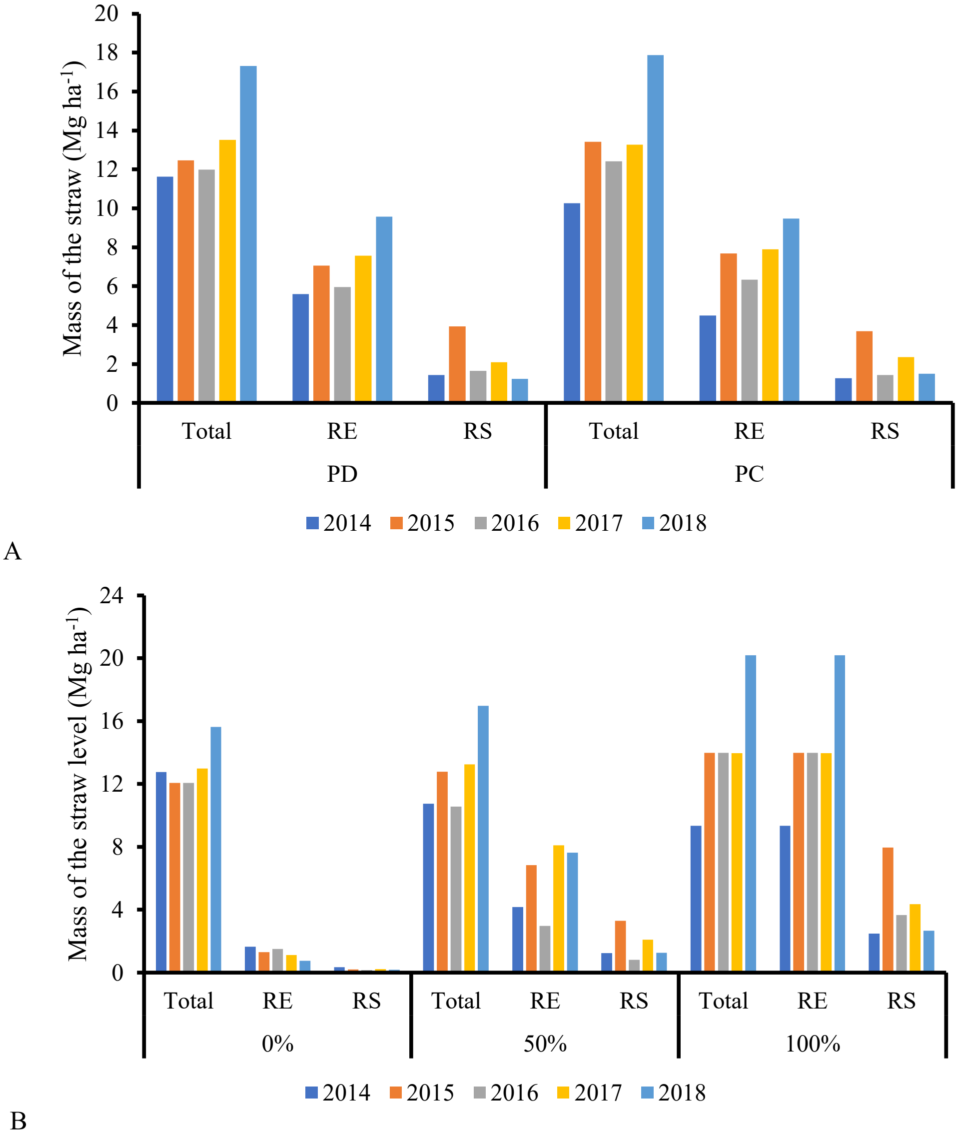


Figure 3. Sugarcane straw mass: total, remaining (RE), and residual (RS), as affected by tillage system (A) and straw retention levels (B). Remaining straw: material remaining on the soil surface immediately after adjusting the straw removal treatments. Residual straw: undecomposed material remaining on the soil surface until the subsequent harvest.

Straw removal was performed by windrowing using a New Holland AL 1290 rake pulled by an 80.9 kW tractor, followed by baling with a New Holland BB 1290 baler pulled by a 132.4 kW tractor. Bales were subsequently retrieved using a New Holland AC 1290 trailer pulled by an 80.9 kW tractor. Partial removal (50% retention) was achieved by adjusting the operating height of the rake.

Soil biological quality

Soil samples were collected from the 0.0–0.10 m soil layer using a Dutch auger; each composite sample comprised four subsamples collected from the central rows of each plot. Sampling was conducted during four periods: October 2015 (to characterize initial conditions during the first ratoon) and three times during the fifth ratoon (September 2018, April 2019, and July 2019). This relatively small interval between sampling events during the fifth ratoon allowed characterization of microbial biomass under contrasting climatic conditions. Soil samples were sieved through a 2.00-mm mesh to remove visible plant residues, organisms, and roots and were subsequently stored in plastic bags and kept in a refrigerated chamber until analysis.

Microbial biomass carbon was determined using the fumigation extraction method (VANCE; BROOKES; JENKINSON, 1987). Carbon was quantified in fumigated and non-fumigated subsamples. Fumigated subsamples were exposed to alcohol-free chloroform vapor for 48 h in a desiccator containing 20 mL of chloroform. Non-fumigated subsamples were extracted immediately after weighing in snap-cap glass vials. Both fumigated and non-fumigated subsamples received 50 mL of 0.5 mol L^{-1} K_2SO_4, were shaken at 150 rpm for 30 min, and the extracts were filtered. Extractable carbon was measured spectrophotometrically at a wavelength of 495 nm (SILVA et al., 2023).

Basal soil respiration (C-CO_2; µg C-CO_2 g^{-1} soil day^{-1}) was measured by incubating soil samples for 7 days in sealed vials in a dark, cool environment with 1 mol L^{-1} NaOH to capture CO_2 released by microorganisms. After incubation, 1% phenolphthalein was added to the NaOH solution, and the captured CO_2 was quantified by titration with standardized 0.5 mol L^{-1} HCl.

The metabolic quotient (qCO_2) was calculated as the ratio of basal respiration (C–CO_2) to microbial biomass carbon (ANDERSON; DOMSCH, 1993). Soil organic carbon (SOC) was determined after sample grinding using the Dumas dry combustion method in a Total Organic Carbon Analyzer (TOC-V) (KALEMBASA; JENKINSON, 1973).

Soil macrofauna was assessed by collecting soil monoliths (0.25 m × 0.25 m × 0.10 m) from the 0–10 cm and 10–20 cm soil layers in each treatment during four sampling periods: September 2018, November 2018, March 2019, and July 2019 (ANDERSON; INGRAM, 1993). These sampling periods were selected to capture macrofauna responses during both dry and rainy seasons in the final ratoon cycle (2018–2019).

Monoliths were immediately hand-sorted, and the extracted organisms were preserved in 70% ethanol. Organisms were identified and counted under a stereomicroscope (40× magnification) in Petri dishes, primarily at the order level and, in some cases, at the family level (ANDERSON; INGRAM, 1993). Because the experiment was long term, most analyses were conducted during the final ratoon cycle (2018–2019) to assess cumulative effects of the tillage systems over five ratoons, with biological assessments concentrated during this period.

Stalk and sugar yields

Stalk and sugar yields were determined at the end of each ratoon: first (2014–2015), second (2015–2016), third (2016–2017), fourth (2017–2018), and fifth (2018–2019). Yield was assessed by manually harvesting two subsamples of 10 marketable stalks each from two locations within the evaluation area of each plot (equivalent to four 15-m rows). Stalk yield (Mg ha^{-1}) was calculated from bundle mass and number of stalks per hectare using proportional extrapolation. Sugar yield (Mg ha^{-1}) was calculated by multiplying stalk yield by total recoverable sugar and dividing by 100 for each experimental unit. Total recoverable sugar was determined by technological analysis following the Brazilian Sugarcane Payment by Sucrose Content System (SPCTS). Accumulated stalk yield and sugar yields were obtained by summing values across the five ratoons. The chronology of experimental procedures is summarized in Figure 4.

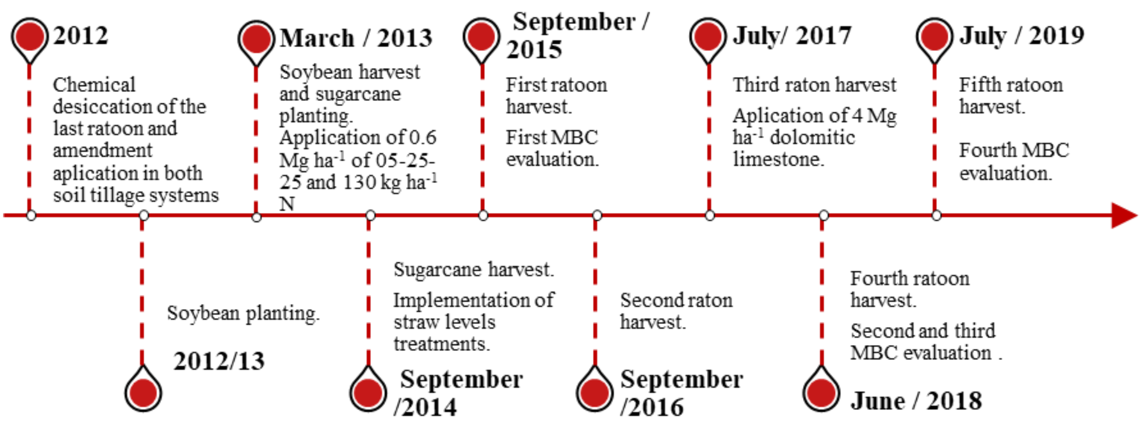


Figure 4. Timeline of experimental procedures.

Statistical analysis

Data for soil microbial attributes, soil macrofauna, accumulated stalk yield, and sugar yield were subjected to analysis of variance (ANOVA), and treatment means were compared using Tukey's test at $P < 0.05$.

RESULTS AND DISCUSSION

Soil biological quality

Microbial biomass carbon (MBC) was affected only by the tillage system in the first two sampling events. In the initial sampling (October 2015), no-tillage exhibited higher MBC (267 µg C g^{-1} dry soil) than conventional tillage (199 µg C g^{-1} dry soil), reflecting minimal soil disturbance under no-tillage (Table 1).

The effects of soil tillage varied among sampling events (Table 2). In September 2018, no-tillage showed significantly higher MBC (211 µg C g^{-1} dry soil), basal respiration (C-CO_2; 24.8 µg C g^{-1} soil day^{-1}), and soil organic matter (SOM; 29.5 g kg^{-1}). In contrast, in April 2019 and July 2019, no significant differences were observed between the soil tillage systems, except for SOM and C-CO_2. The effects of straw retention also differed between sampling events. In October 2015, higher straw retention reduced C-CO_2 (Table 1); in September 2018, none of the variables responded to straw retention. In April 2019 and July 2019, 0% straw retention significantly decreased MBC, qMIC, and SOM (Table 2). Systems with greater surface plant residue cover provide favorable conditions for soil microorganisms through increased moisture, moderated soil temperature, and greater availability of nutrient resources (WANG et al., 2020).

Table 1. Microbial biomass carbon (MBC; µg C g^{-1} dry soil), basal respiration (C-CO_2; µg C-CO_2 g^{-1} soil day^{-1}), metabolic quotient (qCO_2), microbial quotient (qMIC), and soil organic matter (SOM) under no-tillage (NT) and conventional tillage (CT) systems and straw retention levels in October 2015.

Treatment		MBC	C-CO_2	*q*C-CO_2	*q*MIC	SOM
		µg C g^{-1}	µg C-CO_2 g^{-1} day^{-1}	µg C-CO_2 µg^{-1} MBC h^{-1}	%	g kg^{-1}
Tillage system	NT	267 a	25.4 a	48.4 a	1.59 a	28.6 b
	CT	199 b	15.4 b	34.9 a	1.10 b	31.3 a
Straw retention level (%)	0%	187 a	24.8 a	39.8 a	1.11 a	29.4 a
	50%	270 a	19.4 b	30.0 a	1.35 a	29.6 a
	100%	241 a	17.5 c	54.2 a	1.58 a	30.8 a
Tillage × Straw		8.210^{*}	0.149^{ns}	2.731^{ns}	6.167^{*}	0.682^{ns}

Means followed by the same letters within a column for each treatment do not differ significantly by the Tukey's test (P < 0.05). Tillage × Straw interaction: * = significant at P < 0.05, and ns = not significant by the F test.

Table 2. Microbial biomass carbon (MBC; µg C g^{-1} dry soil), basal respiration (C-CO_2; µg C-CO_2 g^{-1} soil day^{-1}), metabolic quotient (qCO_2), microbial quotient (qMIC), and soil organic matter (SOM) under no-tillage (NT) and conventional tillage (CT) systems and straw retention levels in September 2018, April 2019, and July 2019.

Treatment		MBC	C-CO_2	*q*C-CO_2	*q*MIC	SOM
		µg C g^{-1}	µg C-CO_2 g^{-1} day^{-1}	µg C-CO_2 µg^{-1} MBC h^{-1}	%	g kg^{-1}
September 2018						
Tillage system	NT	149 B	20.2 b	60.2 a	0.97 a	26.5 b
	CT	211 A	24.8 a	50.6 a	1.24 a	29.5 a
Straw retention level (%)	0%	196 A	25.7 a	57.7 a	1.18 a	28.3 a
	50%	189 A	18.1 a	42.8 a	1.20 a	26.9 a
	100%	158 A	23.7 a	65.7 a	0.94 a	28.8 a
Tillage × Straw		1.789^{ns}	1.947^{ns}	0.159^{ns}	1.885^{ns}	0.386^{ns}
April 2019						
Tillage system	NT	190 A	23.6 A	55.6 a	1.04 a	31.2 b
	CT	177 A	14.8 B	40.8 a	0.90 a	33.5 a
Straw retention level (%)	0%	132 B	17.7 A	56.7 a	0.74 b	30.8 b
	50%	191 Ab	19.3 A	48.3 a	1.01 ab	32.3 ab
	100%	228 A	20.6 A	39.7 a	1.16 a	33.8 a
Tillage × Straw		0.909^{ns}	2.240^{ns}	3.369^{ns}	0.741^{ns}	0.163^{ns}
July 2019						
Tillage system	NT	233 A	19.7 A	35.0 a	1.28 a	31.2 a
	CT	250 A	20.0 A	36.2 a	1.33 a	32.0 a
Straw retention level (%)	0%	180 C	18.6 B	43.0 a	1.03 c	30.2 b
	50%	233 B	19.3 B	34.6 b	1.31 b	30.8 ab
	100%	310 A	21.6 A	29.3 b	1.58 a	33.8 a
Tillage × Straw		4.339^{*}	1.333^{ns}	2.191^{ns}	2.393^{ns}	0.131^{ns}

Means followed by the same letters within a column for each treatment do not differ significantly by the Tukey's test (P < 0.05). Tillage × Straw interaction: * = significant at P < 0.05, and ns = not significant by the F test.

The tillage × straw retention interaction was significant for MBC in October 2015 and July 2019 and for qMIC in October 2015 (Tables 3 and 4). In both tillage systems, greater straw decomposition occurred under 50% and 100% straw retention. Increased MBC and straw decomposition likely contributed to higher soil organic carbon content, consistent with the higher SOM observed under 100% straw retention from April 2019 onward (Table 2).

Basal respiration ($C\text{-}CO_2$) was higher under conventional tillage in September 2018 and under no-tillage in October 2015 and April 2019; low rainfall (49.6 mm) in April 2019 (Figure 2) may explain this shift, as the more conservative no-tillage system likely maintained more favorable conditions for microorganisms (Table 2). Basal respiration generally reflects overall microbial activity (BOLAT, 2019). According to Gomes et al. (2021), microbial biomass decreases substantially during the dry season, whereas soil moisture increases during the rainy season and surviving organisms use accumulated soil organic matter, resulting in higher microbial activity. In July 2019, the highest basal respiration under 100% straw retention (21.6 µg $C\text{-}CO_2$ g^{-1} soil day^{-1}) did not indicate carbon loss, as it coincided with elevated MBC, suggesting increased microbial efficiency (Table 2).

The tillage × straw retention interaction was significant for microbial biomass carbon (MBC) in October 2015 and July 2019 (Table 3). In October 2015, MBC increased under straw retention levels of 50% and 100% only under no-tillage, consistent with reduced soil disturbance under no-tillage systems. In contrast, by July 2019, higher straw retention significantly increased MBC in both tillage systems, even during winter, when microbial activity typically declines. Thus, straw retention maintained a favorable microenvironment, enabling efficient microbial decomposition and nutrient cycling even under low-temperature conditions (WANG et al., 2020).

No significant effects of tillage or straw retention on the metabolic quotient (qCO_2) were observed until the third sampling (April 2019), whereas a significantly higher qCO_2 (43.0 µg $C\text{-}CO_2$ µg^{-1} MBC h^{-1}) was observed under 0% straw retention in the fourth sampling (July 2019) (Table 2). Lower qCO_2 in more stable systems indicates higher metabolic efficiency, reflecting reduced carbon expenditure for microbial maintenance compared to communities subjected to disturbance (BOLAT, 2019; SOUZA et al., 2006).

Similarly, Almeida et al. (2015) reported higher qCO_2 in irrigated sugarcane cultivation systems without straw retention. Lower qCO_2 indicates greater agroecosystem stability, resulting from efficient resource use by MBC, reduced basal respiration ($C\text{-}CO_2$) losses, and greater carbon incorporation into microbial biomass (SILVA et al., 2015; KOUDAHE; ALLEN; DJAMAN, 2022). Straw retention significantly affected the microbial quotient (qMIC) after five years (April and July 2019), with the highest values observed under 100% retention (1.16% in April 2019 and 1.58% in July 2019) (Table 2). Higher qMIC reflects greater carbon availability to microorganisms in systems with higher organic matter content (ALMEIDA et al., 2015).

The tillage × straw retention interaction was significant for qMIC only in October 2015 (Table 4). Higher qMIC under partial or full straw retention was primarily associated with increases in MBC. The microbial quotient (qMIC), calculated as the ratio of MBC to SOM, indicates the proportion of organic carbon immobilized in microbial biomass and therefore the efficiency of soil carbon accumulation (ANDERSON; DOMSCH, 1993).

Table 3. Microbial biomass carbon (MBC) under no-tillage and conventional tillage systems and straw retention levels in October 2015 and July 2019.

Soil tillage	MBC (µg C g^{-1} dry soil)		
	0% straw retention	50% straw retention	100% straw retention
	October 2015		
No-tillage	182.40 aB	323.88 aA	293.72 aA
Conventional	192.47 aA	215.63 bA	188.19 aA
	July 2019		
No-tillage	183.38 aC	222.71 aB	291.84 aA
Conventional	177.47 aC	244.15 aB	329.02 aA

Means followed by the same lowercase letters within a column, or uppercase letters within a row, do not differ significantly by the Tukey's test ($P < 0.05$).

Table 4. Microbial quotient (qMIC) under no-tillage and conventional tillage systems and straw retention levels in October 2015.

Soil tillage	*q*MIC (%)		
	0% straw retention	50% straw retention	100% straw retention
	October 2015		
No-tillage	1.07 aB	1.27 bAB	1.50 aA
Conventional	0.99 aB	1.35 aA	1.68 aA

Means followed by the same lowercase letters within a column, or uppercase letters within a row, do not differ significantly by the Tukey's test ($P < 0.05$).

Soil organic matter (SOM) responds slowly to management changes and is therefore typically evaluated over long periods. In the first three sampling events, SOM was significantly higher under conventional tillage (31.3, 29.5, and 33.5 g kg⁻¹) than under no-tillage (28.6, 26.5, and 31.2 g kg⁻¹); by the final sampling (July 2019), differences were not significant (Table 2). Greater soil disturbance under conventional tillage likely accelerated decomposition of incorporated plant residues, temporarily increasing mineralization and SOM in the short term (SILVA et al., 2023).

Soil macrofauna

Soil biological quality evaluation requires the use of multiple indicators, including macrofauna, which respond sensitively to anthropogenic disturbances. Faunal attributes assessed were density (individuals m⁻²) and richness (number of taxonomic groups). In September 2018, no significant treatment effects or interactions were observed at either soil layer (Table 5); significant interactions were observed in the subsequent sampling events (November 2018, March 2019, and July 2019).

Table 5. Density (individuals m⁻²) and richness (number of taxonomic groups) of soil macrofauna under no-tillage (NT) and conventional tillage (CT) systems and straw retention levels across four sampling events at the 0–10 cm and 10–20 cm soil layers.

Treatment		Sampling soil layers			
		0–10 cm		10–20 m	
		Richness (number of groups)	Density (individuals m^2)	Richness (number of groups)	Density (individuals m^2)
September 2018					
Tillage system	NT	2.08 a	9.33 a	1.16 a	2.58 a
	CT	2.33 a	10.00 a	1.25 a	11.58 a
Level of straw (%)	0	1.87 a	5.00 a	1.12 a	2.25 a
	50	2.25 a	8.37 a	1.37 a	6.25 a
	100	2.50 a	15.62 a	1.12 a	12.75 a
Tillage × Straw		1.235^{ns}	0.339^{ns}	0.593^{ns}	0.907^{ns}
November 2018					
Tillage system	NT	3.58 b	7.7b b	2.33 b	20.66 b
	CT	3.66 a	13.91 a	2.58 a	22.58 a
Level of straw (%)	0	3.87 a	6.25 c	2.37 b	18.37 b
	50	3.75 b	9.75 b	2.87 a	30.00 a
	100	3.25 c	16.50 a	2.12 c	16.50 c
Tillage × Straw		0.259*	301.03*	3.111*	6.259*
March 2019					
Tillage system	NT	4.33 a	17.75 b	3.58 a	25.41 b
	CT	4.16 b	33.91 a	3.16 b	30.58 a
Level of straw (%)	0	4.37 a	21.12 c	3.37 b	21.12 c
	50	4.37 a	27.00 b	3.75 a	35.37 a
	100	4.00 b	29.37 a	3.00 c	27.50 b
Tillage × Straw		0.037*	391.37*	0.481*	23.593*
July 2019					
Tillage system	NT	4.16 a	20.91b	4.08 a	15.91 b
	CT	3.83 b	24.50 a	3.83 b	21.41 a
Level of straw (%)	0	4.12 a	21.75 c	4.00 a	13.12 C
	50	4.00 b	22.37 b	3.87 b	19.50 b
	100	3.87 c	24.00 a	4.00 a	23.37 a
Tillage × Straw		0.259*	91.593*	0.111*	30.333*

Means followed by the same letters within a column for each treatment do not differ significantly by the Tukey's test ($P < 0.05$). Tillage × Straw interaction: * = significant at $P < 0.05$, and ns = not significant by the F test. Mean test applied to data transformed by $\sqrt{(x)}$.

Low macrofauna density in September 2018 resulted from recent mechanized harvesting and straw removal disturbances; recovery is typically slower in intensive monoculture systems. Climatic conditions also contributed to the absence of tillage system effects, as the September 2018 sampling reflected macrofauna populations after winter, characterized by low temperatures and rainfall (Figure 2), which potentially limited organism activity. In contrast, greater macrofauna abundance often occurs in summer due to higher rainfall and temperatures, which enhance activity related to feeding and reproduction (PEREIRA et al., 2020).

Main effects of tillage and straw retention revealed differences in macrofauna density and richness. In the final two sampling events (March and July 2019), conventional tillage exhibited higher density and lower richness at both the 0–10 cm and 10–20 cm soil layers; in contrast, in November 2018, conventional tillage showed higher density and richness across the 0–20 cm soil profile. The increased macrofauna under conventional tillage in November 2018 likely resulted from the recent mechanized harvest (July 2018), which altered surface cover and soil moisture. Soil moisture fluctuations can influence vertical and horizontal distribution and abundance of soil invertebrates (NUNES et al., 2012). Under such conditions, macrofauna communities are often in a colonization phase, lacking a stable structure, and metrics such as density and richness may fluctuate considerably before stabilization (NUNES et al., 2012). This pattern was particularly evident under 0% straw retention, which consistently showed higher density but lower richness across the last three sampling events (November 2018, March 2019, and July 2019) (Table 5).

The tillage × straw retention interaction was significant for macrofauna richness and density at both soil layers in November 2018, March 2019, and July 2019 (Tables 6 and 7). In November 2018, conventional tillage with straw cover showed greater richness and density at both soil layers; in subsequent sampling events, conventional tillage generally exhibited higher density, whereas no-tillage showed higher richness.

Table 6. Richness (number of taxonomic groups) of soil macrofauna under no-tillage (NT) and conventional tillage (CT) systems and straw retention levels across three sampling events (November 2018, March 2019, and July 2019) at the 0–10 cm and 10–20 cm soil layers.

Tillage system	Straw retention level (%)					
	0	50	100	0	50	100
	0 – 10 cm			10 – 20 cm		
	November 2018					
NT	4.00 aA	3.75 bB	3.25 aC	3.25 aA	2.75 bB	1.75 bC
CT	3.75 bB	4.00 aA	3.25 aC	1.50 bC	3.00 aA	2.50 aB
	March 2019					
NT	4.50 aA	4.50 aA	4.00 aB	3.50 aB	3.75 aA	3.50 aB
CT	4.25 bA	4.25 bA	4.00 aB	3.25 bB	3.75 aA	2.50 bC
	July 2019					
NT	4.50 aA	4.00 aB	4.00 aB	4.25 aA	4.00 aB	4.00 aB
CT	3.75 bB	4.00 aA	3.75 bB	3.75 bB	3.75 bB	4.00 aA

Means followed by the same lowercase letters within a column, or uppercase letters within a row, do not differ significantly by the Tukey's test (P < 0.05). Mean test applied to data transformed by √(x).

Table 7. Density (individuals m⁻²) of soil macrofauna under no-tillage (NT) and conventional tillage (CT) systems and straw retention levels across three sampling events (November 2018, March 2019, and July 2019) at the 0–10 cm and 10–20 cm soil layers.

Tillage system	Straw retention level (%)					
	0	50	100	0	50	100
	0 – 10 cm			10 – 20 cm		
	November 2018					
NT	9.50 aA	7.00 bB	6.75 bC	16.50 aB	30.00 aA	15.50 bC
CT	3.00 bC	12.50 aB	26.25 aA	20.25 bB	30.00 aA	17.50 aC
	March 2019					
NT	16.75 bB	23.75 bA	12.75 bC	20.00 bC	30.75 bA	25.50 bB
CT	25.50 aC	30.25 aB	46.00 aA	22.25 aC	40.00 aA	29.50 aB
	July 2019					
NT	23.00 aA	21.50 bB	18.25 bB	10.20 bC	22.75 bA	14.75 bB
CT	20.50 bC	23.25 aB	29.75 aA	16.00 aC	24.00 aB	24.25 aA

Means followed by the same lowercase letters within a column, or uppercase letters within a row, do not differ significantly by the Tukey's test (P < 0.05). Mean test applied to data transformed by √(x).

Richness interactions revealed stronger effects of 0% straw retention under no-tillage, with higher richness than the other levels in most sampling events, except March 2019 (Table 6). Under conventional tillage, 50% straw retention increased richness and density relative to 0% retention in the 0–10 cm soil layer in November 2018 and July 2019, and in the 10–20 cm in November 2018 and March 2019 (Tables 6 and 7). In July 2019, 100% straw retention under conventional tillage resulted in the highest values, except for richness in the 0–10 cm soil layer (Tables 6 and 7).

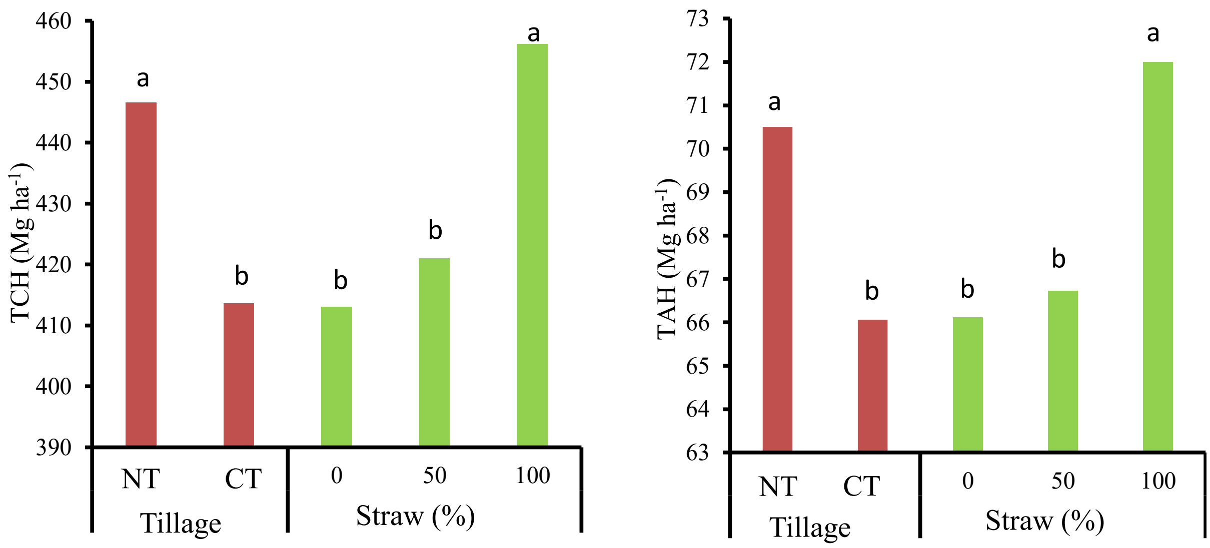
Straw retention generally enhanced macrofauna occurrence across tillage systems; however, under no-tillage, total straw removal increased density, likely due to the limited influence of straw quantity on richness and diversity indices in certain systems (ABREU et al., 2014).

At the 10–20 cm soil layer, 50% straw retention resulted in the highest density in November 2018 and March 2019, whereas 100% straw retention resulted in the highest macrofauna density in July 2019 under conventional tillage. Conventional tillage exhibited higher macrofauna density under 100% straw retention in November 2018 and across all straw levels in March and July 2019 (Table 7). The highest density (40.0 individuals m^{-2}) occurred under 50% straw retention with conventional tillage in March 2019.

Similarly, Franco et al. (2016) reported increased macrofauna diversity under ≥50% straw retention in sugarcane cultivation at deeper soil layers, attributable to an improved microclimate. Higher macrofauna density under conventional tillage at the 10–20 cm in the final two sampling events likely reflected improved soil physical structure following initial tillage disturbances, enhancing macropore formation and organism movement (Table 7).

Sugarcane yield

Main effects of tillage and straw retention were significant for accumulated stalk yield and sugar yield over the five ratoons (Figure 5).



Bars with the same letter within each treatment do not differ significantly (Tukey's test, P < 0.05).

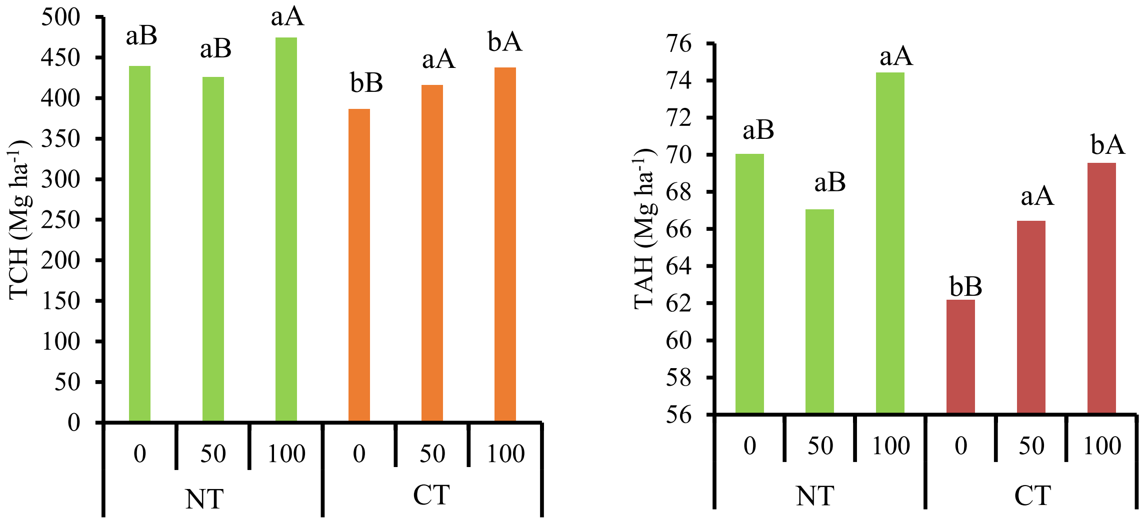
Figure 5. Accumulated stalk yield (Mg ha^{-1}) and sugar yield (Mg ha^{-1}) from 2014 to 2019 under no-tillage (NT) and conventional tillage (CT) systems and straw retention levels.

Stalk yield was higher under the no-tillage system (447 Mg ha^{-1}), exceeding that under conventional tillage by 33 Mg ha^{-1}. Across straw retention levels, 100% retention resulted in the highest stalk yield (456 Mg ha^{-1}), which was 43 Mg ha^{-1} greater than that under 0% retention (413 Mg ha^{-1}). Sugar yield followed the same trend, with no-tillage and 100% straw retention resulting in the highest values.

Mean annual stalk yield under 100% straw retention reached 91 Mg ha^{-1}, approximately 24% higher than the regional average for the previous four cycles in Mato Grosso do Sul (73.3 Mg ha^{-1}) (CONAB, 2024). These results indicate the benefits of combining no-tillage with full straw retention for maintaining high yields.

Similarly, Bordonal et al. (2018) reported substantial reductions in stalk yield with complete straw removal in clay-textured soils, with accumulated losses of 28-62 Mg ha^{-1} across experiments, but no effect in low-fertility sandy soils. These lower yields under total straw removal were attributed to low rainfall during harvest periods reducing soil moisture during initial crop development. This pattern was also observed in the present study from the 2015–2016 harvest, when rainfall during harvest periods were relatively low (Figure 2).

Soil tillage systems and straw retention levels had similar effects on accumulated sugar yield and accumulated stalk yield (Figure 6). No-tillage with 100% straw retention achieved the highest sugar yield (74 Mg ha^{-1}), approximately 4.0 Mg ha^{-1} higher than under 0% straw retention. The lowest sugar yield was observed under conventional tillage with 0% straw retention (62 Mg ha^{-1}).



Bars with the same lowercase letter (comparing tillage systems within straw retention levels) or uppercase letter (comparing straw retention levels within tillage systems) do not differ significantly (Tukey's test, $P < 0.05$).

Figure 6. Accumulated stalk yield (Mg ha^{-1}) and sugar yield (Mg ha^{-1}) from 2014 to 2019 under no-tillage (NT) and conventional tillage (CT) systems and straw retention levels.

Higher stalk and sugar yields under 100% straw retention are consistent with findings reported by Castioni et al. (2019), who observed increased yields with 10–15 Mg ha^{-1} of straw retained over four years compared with partial or total removal. Similarly, Melo et al. (2020) reported that retention of 8–13 Mg ha^{-1} of straw maintained favorable soil physical conditions for root growth and increased sugarcane yield.

Although straw retention effects on soil microbiota and macrofauna were not pronounced in this study, the practice increased soil fertility (higher K and organic matter contents in the surface soil layer) and improved physical quality (reduced compaction) over the crop cycle, as reported by Arcoverde et al. (2023).

CONCLUSION

The soil tillage systems evaluated over a full sugarcane crop cycle (five ratoons) with partial (50%) or total (100%) straw retention improved soil microbial quality, significantly increasing microbial biomass carbon and the microbial quotient.

Under conventional tillage, partial or total straw retention improved soil biological quality through significant increases in macrofauna density and richness.

Combining no-tillage with 100% straw retention significantly increased stalk and sugar yields throughout the sugarcane crop cycles.

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