Can reduced tillage sustain sugarcane yield and soil carbon if straw is removed?

Sarah Tenelli^{1,2} · Ricardo de Oliveira Bordonal¹ · Leandro Carneiro Barbosa¹ · João Luis Nunes Carvalho¹

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Abstract

Straw removal for bioelectricity, cellulosic ethanol, or other bio-products has become a common practice in Brazilian sugarcane areas, but long-term effects on soil organic carbon (SOC) and yield are unknown. Our objective was to quantify tillage intensity and removal levels on SOC stocks and sugarcane yield on contrasting edaphoclimatic conditions in Brazil. Conventional tillage-CT and reduced tillage-RT coupled with three straw removal levels (none—NR; moderate—MR; total—TR) were combined to create six treatment combinations: CTNR, CTMR, CTTR, RTNR, RTMR, and RTTR, respectively. Sugarcane yield was measured annually and soil samples to a depth of 40 cm were collected and analyzed before and after 5 years of treatments. Neither tillage practices nor straw removal significantly affected sugarcane yield on sandy loam soil, but CTMR, CTTR, and RTTR showed substantial yield reductions on clayey soil. SOC stocks for RTNR increased by as much as 1.64 Mg ha⁻¹ year⁻¹ on clayey soil, while CTMR and CTTR favored depletion of SOC stocks on both soils. Overall, each Mg of straw returned to the soil increased SOC stock by 95 kg ha⁻¹ for clayey soil under both tillage practices and 55 kg ha⁻¹ for sandy loam under the CT system. Furthermore, straw removal decreased microbial biomass C and b-glucosidase activity. These findings suggest that the adoption of RT attenuates the adverse impacts of straw removal on SOC stocks while ensuring sugarcane yields for a more sustainable bioenergy production in Brazil.

Keywords Tillage systems · *Saccharum* spp. · Soil enzymatic activity · Microbial biomass carbon · Soil organic matter · Crop residues

Introduction

Sustainable management practices have a major effect on sustaining soil organic carbon (SOC) while providing renewable-based energy resources to biofuel feedstocks and contribute to carbon (C) sequestration from the atmosphere [1]. To meet the international commitments assumed at the Paris Convention

of the Parties (COP 21) in supplying global targets for bioenergy, the Brazilian government intends to increase ethanol production by 50 billion liters per year by 2030 [2], which is 79% higher than it was produced in 2015. In the view of biofuel programs that can help reduce the C footprint of ethanol, Brazil stands out already as a low C economy, including today an energy mix of 40% of renewables and cogeneration of electricity from biomass [3]. Brazil is the major producer of sugarcane (*Saccharum* spp.) with a production of 660 million tons from a cultivated area of 8.6 million ha in the 2018/2019 season [4].

Sugarcane is a crop that is grown in a 5- to 6-year cycle of yearly harvests. With the historical replacement of sugarcane burning prior to harvest, a significant amount of straw (i.e., 10–20 Mg ha⁻¹ of dry mass) is now deposited on the soil surface annually [5]. Sugarcane straw (also known as trash) consists mainly of green tops and dry leaves [5]. The high-energy potential of sugarcane is very competitive in relation to fossil fuels and can be a consistent source of replacement to mitigate greenhouse gas (GHG) emissions [6]. The sugarcane stalk compartment is the raw material used for 1G ethanol

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✉ João Luis Nunes Carvalho
joao.carvalho@ctbe.cnpem.br

¹ Brazilian Biorenewables National Laboratory (LNBR), Brazilian Center of Energy and Material Research (CNPem), Giuseppe Maximo Scolfaro Street, 10000, Campinas, SP 13083-100, Brazil

² Interdisciplinary PhD. Program in Bioenergy, University of Campinas (UNICAMP), Rua Monteiro Lobato, 80, Cidade Universitária, Campinas, SP 13083-862, Brazil

production, in which from the juice is produced sugar and ethanol and the remainder of bagasse is a source currently used for bioelectricity generation. The straw compartment represents one-third of the total sugarcane energy that can be potentially used for bioenergy production [7]. Because of the possible conversion of sugarcane straw into cellulosic biofuels, bioelectricity, and other bio-products, new approaches to straw biomass management have emerged in Brazilian sugarcane fields [8]. However, a lot of controversy remains about the amount of straw that can be sustainably removed to sustain soil ecosystem services [9], which is highly variable and is a function of multiple aspects including crop aging, soil characteristics, climatic conditions, and agriculture practices [10].

Maintaining sugarcane straw in the field supports soil biota as a source of nutrients, shelter, and better microclimate conditions, which promote increases in microbial biomass [11]. Indiscriminate removal of sugarcane straw from the field can intensify the risk of soil erosion [12] and has detrimental effects on numerous soil quality indicators [9], including SOC stocks [10, 13, 14], microbial activity [11, 15], soil structure [16], plant-nutrient recycling [17], weed infestation [5], soil thermal regulator, and water storage [18, 19]. On the other hand, keeping excessive amounts can retard ratoon tillering in some specific regions [20], promote an ideal microclimate for pests and diseases development [7], and increase N₂O emissions to the atmosphere [21]. Such a concern associated with the straw management challenges is not restricted to sugarcane straw in Brazil but is rather a subject of research emerging in other locations using corn stover in the USA [22] and wheat in Europe [23].

Although the use of straw represents a valuable asset for bioenergy production and could provide short-term economic gains for farmers, the removal of this crop residue may decrease SOC stocks, thus reducing part of the environmental and agronomic benefits. Recent studies have indicated that sugarcane straw is an important source of C to the soil, and consequently, the indiscriminate removal of this crop residue will result in depletion of SOC stocks [10, 14, 24], which can negatively affect the GHG balance of sugarcane ethanol production [14].

In most areas under sugarcane production in Brazil, the straw remains on the soil surface and conventional tillage (CT) is still performed during the crop replanting period, and therefore, this management can potentially reduce the benefits of straw retention in SOC accretion [25]. Reduced tillage (RT) plays an essential role as an environmental and economical viable management [26] to reduce GHG emissions associated with tillage operations in the sugarcane mechanized system [27]. In this context, a transition to conservationist management practices such as the RT system could be a feasible management target to enhance SOC sequestration in sugarcane fields [28].

Losses of SOC stocks play an important role for monitoring land and soil degradation [29]. Monitoring SOC stocks is critical to underpin strategies of management for sustaining key soil functions [30], so that the integrated use of RT coupled with straw removal should be further investigated as a management target to potentially offset SOC losses [24]. Although recent studies modeled SOC changes induced by straw removal in Brazilian sugarcane fields [13, 14], there are no studies assessing in-field SOC changes induced by levels of straw removal in sugarcane areas under different tillage systems in Brazil. This study was based on the hypothesis that (i) the removal of straw in CT management intensifies SOC losses and does not reflect in higher sugarcane yield relative to the RT system and (ii) the RT under moderate and no-removal of straw is a management target for enhancing SOC stocks and sustaining sugarcane yields over the crop cycle. This study was designed to evaluate the changes in SOC stocks affected by contrasting straw removal levels and tillage systems in two sugarcane fields with different soil textures in south-central Brazil. Our focus was also to quantify the impacts of straw removal on soil microbial biomass C and β -glucosidase activity under the RT system. The specific objective was to assess the potential of RT as a management strategy to offset the adverse effects of straw removal on SOC stocks and ensure a viable sugarcane yield.

Material and methods

Characterization of study areas

Two field trials were installed in December 2012 in commercial sugarcane farms located in Quatá, São Paulo (SP) state, and Quirinópolis, Goiás (GO) state. According to Soil Survey Staff [31], Quatá/SP has an arenic Kandudult soil with sandy loam texture and a climate classified as C1wa'a', which is a dry to sub-humid climate with moderate hydric excess in the summer [32]. Quirinópolis/GO has a Rhodic Eutrudox soil with clayey texture and a climate defined as B1wa'a', which is a humid climate with moderate water deficiency in the winter. Descriptions of land use and management changes in both areas before the experiment setup and the soil physical and chemical characterization in 2012 are presented in Table 1.

Experimental design and treatments

Before the field experiments setup (October 2012), each location was under the fifth sugarcane ratoon cycle, and thus it was submitted to a renovation period by spraying glyphosate (6 L ha⁻¹), followed by applications of lime (2 Mg ha⁻¹) and gypsum (1 Mg ha⁻¹). A cover crop with sunn hemp (*Crotalaria spectabilis*) was planted in December 2012 at a rate of 25 kg seed ha⁻¹ and herbicides were used to desiccate it (5 L ha⁻¹ of

Table 1 Soil characterization of the sites before experiments establishment in 2012 in sandy loam soil and clayey soil

Sites description	Sandy loam soil	Clayey soil
Location (city/state)	Quatá/São Paulo	Quirinópolis/Goiás
Geographic coordinates	22° 14' S; 50° 42' W	18° 32' S; 50° 26' W
Elevation (m)	541	460
Mean annual precipitation (mm)	1254	1520
Mean annual temperature (°C)	20.8	22.5
Previous land use	Pasture	Pasture
Conversion of pasture to sugarcane	1995	2006
Adoption of burned harvesting	1995–2009	—
Adoption of green mechanized harvesting	2009	2006
Chemical attributes (0–40 cm) ^a		
pH CaCl ₂	4.8	5.6
SOM (g dm ⁻³)	12	46
P (mg dm ⁻³)	15	8
K (mmol _c dm ⁻³)	0.4	3.7
Ca (mmol _c dm ⁻³)	12	38
Mg (mmol _c dm ⁻³)	3.6	11
CEC (mmol _c dm ⁻³)	32	75
BS (%)	48	71
Physical attributes (0–40 cm) ^b		
Clay/silt/sand content (g kg ⁻¹)		
0–10 cm	87/60/853	547/186/267
10–20 cm	108/60/832	561/190/249
20–40 cm	142/57/801	580/195/225
Soil bulk density (Mg m ⁻³)		
0–10 cm	1.76	1.37
10–20 cm	1.77	1.29
20–40 cm	1.76	1.23

SOM, soil organic matter; CEC, cation exchange capacity; BS, base saturation. ^{a,b} Soil physical and chemical analyses according to Van Raij et al. [33] and Blake and Hartge [34]

glyphosate, 1.2 L ha⁻¹ of 2,4-D, and 0.5 L ha⁻¹ of triamax) at the flowering stage in March/April 2013. After 15 days, two treatments composed of tillage systems were established in a randomized block design with four repetitions. The tillage systems are described as follows: (1) reduced tillage (RT), in which soil preparation was not performed and only planting furrows was opened at a 0.30-m soil depth over the cover crop biomass using a 2-row planter with spacing of 1.5 m; (2) conventional tillage (CT), which was characterized by cross subsoiling using a subsoiler of 5 rows at 0.40-m depth spaced 0.5 m, a light hydraulic harrowing with harrow of 36 disks at 0.20 m and the opening of planting furrows at 0.30-m depth; all practices were performed using a 4 × 4 tractor of 220cv. More details of tillage systems are found in Fig. 1. Sugarcane was planted manually 1 day after tillage practices by placing 15–20 buds per meter using the RB96-6928 variety. Each plot was composed of 10 sugarcane rows at 1.5 m spacing with 10 m long by 15 m wide. At the base of the planting furrow, fertilizers were applied at a rate of 40 kg N ha⁻¹, 125 kg P₂O₅ ha⁻¹ and 125 kg K₂O ha⁻¹.

Thereafter the harvesting of plant-cane cycle in June 2014, three additional treatments of straw management were established in a randomized block design with four repetitions. The straw management comprised of the following removal levels: (i) no-removal—NR; (ii) moderate removal—MR (50% of total produced), and (iii) total removal—TR. Therefore, the experimental design consisted of six treatment combinations, namely CTNR, CTMR, CTTR, RTNR, RTMR, and RTTR. Straw removal levels were established based on the amount of straw produced at each site, which was estimated randomly inside the field trial using a square (0.25 m² at six points per area), weighed, and the moisture was quantified using the sensor AL-104 Agrologic® with E-831 Electrode to assess the results in dry basis. The MR plots were divided into two symmetrical sections, one which all the straw was completely removed and the straw from the other part was uniformly distributed over both sections to yield 50% straw cover across the entire plot. In the TR plots, all straw removed. Same proceedings were performed for the subsequent ratoons each year (Fig. 2). The total amount of straw (in dry basis)

Fig. 1 Description of conventional tillage-CT and reduced tillage-RT characteristics adopted in the field experiment. ■ - dark gray color represents soil disturbed during soil tillage practices; ■ - black represents soil disturbed by soil tillage practices plus planting furrow opening; □ - light gray represents soil disturbed only by planting furrow opening, and □ - white is soil undisturbed

produced in plant-cane first, second, and third ratoons in the two sites were as follows: 16.5, 17.2, 17.2, and 13.4 Mg ha⁻¹ in the clayey soil and 9.2, 12.6, 7.5, and 7.5 Mg ha⁻¹ in sandy loam soil. The fertilization of sugarcane ratoon cycles was applied 60 days after each harvest, above the straw layer and 10 cm away from crop row, using the following sources: ammonium nitrate (32% N, rate of 120 kg N ha⁻¹) and potassium chloride (60% K₂O; 120 kg K₂O ha⁻¹). The control of pests, diseases, and weed was conducted similarly in all treatments according to management practices of each sugarcane mill. The daily temperature, solar radiation, rainfall, wind speed, and relative humidity data were collected from a meteorological station next to the experimental fields. The climatological water balance (Fig. 3) was computed according to the methods proposed by Thornthwaite and Mather [35].

Soil measurements and calculations

Soil sampling was performed after the harvesting of the fourth ratoon in July 2018 (Fig. 2). Composite soil samples were collected from the sugarcane row and inter-row positions at 0–5-, 5–10-, 10–20-, and 20–40-cm depths for SOC concentration analysis. The samples were air-dried, after 10 g was

ground, sieved using a 0.150-mm mesh sieve, and then analyzed by dry combustion using a carbon analyzer—LECO CN 628. In order to calculate SOC stocks, undisturbed soil samples were collected using volumetric rings (diameter 0.05 m × height 0.05 m) for bulk density (BD) determination. Then, the samples were weighed before and after oven drying at 105 °C to determine dry-weight basis. The BD (Mg dm⁻³) was calculated by dividing the soil dry mass by the cylinder volume.

SOC stocks for the 0–10- and 0–40-cm layers were calculated as the sum of the stocks for each depth: 0–5, 5–10, 10–20, and 20–40 cm. In order to adjust SOC stocks to an equivalent soil mass, the BD of the baseline characterization (Table 1) was used as a reference to adjust the depths of the treatments CTNR, CTMR, CTTR, RTNR, RTMR, and RTTR according to the methodology described in Ellert and Bettany [36]. The rates of SOC loss and accumulation (Mg C ha⁻¹ year⁻¹) associated with each treatment (CTNR, CTMR, CTTR, RTNR, RTMR, RTTR) in the last year of evaluation were calculated for the 0–10- and 0–40-cm depths according to equation: (SOC stock_{final} (fourth ratoon) – SOC stock_{initial} (baseline))/5 years, in order to represent changes in SOC stocks (Mg ha⁻¹) induced by the straw removal levels and tillage systems in relation to the reference SOC stock before the trial setup in 2012.

Fig. 2 Timeline description of the installation, harvesting, straw management, and soil evaluation of the experimental areas

Fig. 3 Water balance accounted for the two sites (sandy loam soil—Quatá/SP; clayey soil—Quirinópolis/GO) during the sugarcane crop cycle

In order to explore a deeper understanding of SOC accumulation induced by the cumulative effects of different amounts of straw, samples for microbial biomass C (MBC) and β -glucosidase activity analyses were collected in the RTNR, RTMR, and RTTR treatments. The analyses of MBC were performed by the fumigation-extraction method [37] from a 0–10-cm soil depth. For the same soil samples, the activity of β -glucosidase enzyme was evaluated according to Tabatabai [38]. The microbial quotient (q_{MIC}) expressed by the ratio of MBC to SOC is related to how much SOC is immobilized in the microbial biomass (i.e., a measure of carbon availability). The microbial quotient (q_{MIC}) was calculated by the ratio between MBC and SOC [39].

Measurements of sugarcane stalk yields

Sugarcane crop was annually harvested between June and July for 5 years of the study in Quatá/SP and Quirinópolis/GO. Each plot was harvested by a mechanical harvester and stalk yields were computed for the four central rows through an instrumented truck equipped with a loading cell (used exclusively for experiments).

Statistical analyses

After the normality verification according to the Shapiro-Wilk test at 5% of significance and homogeneity of variance by the Oneill and Mathews test, the data was subjected to analysis of variance (ANOVA) to assess differences among the six treatments of straw removal under tillage systems and the average results were compared using Tukey's test ($p < 0.05$). The

statistical analysis was performed according to a randomized block design with six treatments and four repetitions. In order to isolate the effects of tillage system and straw removal on sugarcane yields, a separate comparison between the means of CT and RT systems was performed to obtain the effects regardless of straw removal levels, as well as for comparisons between means of straw removal levels regardless of tillage systems. Regression analyses were performed to explore the relationships between SOC stocks and straw inputs in both tillage systems in the 0–10-cm soil depth. All statistical analyses were performed using the R Development Core Team [40].

Results

SOC concentration and stocks and annual rates of SOC accumulation/loss

The data indicated that SOC concentration was reduced along the soil profile, with concentrations varying from 1.9 to 7.8 g kg⁻¹ in the sandy loam soil and 13.3 to 29.4 g kg⁻¹ in the clayey soil. High levels of straw removal in both tillage systems reduced SOC concentration in the 0–5- and 20–40-cm depth in both soils (Fig. 4).

Tillage systems and straw removal levels significantly affected SOC concentration in both soils ($p < 0.05$). In sandy loam soil, the treatment RTNR was different from CTTR by 3.1 g kg⁻¹, while the other treatments did not show any differences ($p < 0.05$). Similar patterns were observed in the clayey soil, where RTNR showed higher SOC concentration

Fig. 4 SOC concentration (g kg^{-1}) to a 40-cm depth (0–5, 5–10, 10–20, and 20–40 cm) under tillage systems coupled with straw removal levels (CTNR, CTMR, CTTR, RTNR, RTMR, RTTR) in the sandy loam (a) and clayey (b) soils. Data are means from four sampling replicates. Bars refer to the least significant difference between data and asterisk indicates significant differences among the treatments ($p < 0.05$)

relative to CTTR ($p < 0.05$). Changes in SOC concentration in the 20–40 cm tended to be consistent with the surface layer. SOC was significantly higher for RTNR and RTMR treatments compared to CTMR and CTTR in the sandy loam soil. Meanwhile, SOC differences in the clayey soil presented higher values (3.7 g kg^{-1}) in RTTR than CTNR treatment.

The data obtained herein indicate that significant depletions of SOC stocks were evident when the straw was removed from the field in both soils in the top layer (Fig. 5). For sandy loam soil, straw removal levels did not show differences under CT, but SOC stocks in RTMR and RTTR were lower than RTNR ($p < 0.05$). In addition, SOC stock under RTNR was superior by 1.9 Mg ha^{-1} than the mean values of RTMR, CTNR, CTMR, and CTTR. For clayey soil, SOC stock under RTNR was higher than CTTR by 5.8 Mg ha^{-1} . At the 0–40-cm depth, significant effects on SOC stocks were evident only in the sandy loam, showing similar SOC stocks under RTNR, RTTR, and CTNR, which were 5.1 Mg ha^{-1} higher than CTTR.

Our findings indicate that performing RT at sugarcane planting led to positive SOC sequestration rather than disturbing the soil through CT in the 0–40-cm profile, even when all the straw was removed from the field (Fig. 6). In clayey soil, the adoption of RT resulted in average rates of SOC accumulation (0–40 cm) of 1.64 , 1.03 , and $1.43 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ for RTNR, RTMR, and RTTR compared with baseline, respectively. In contrast, CT systems showed average rates of SOC loss of -0.05 , -0.18 , and $-0.50 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ for CTNR, CTMR, CTTR, respectively. In sandy loam soil, the RT treatments presented SOC accumulation (0–40 cm) of 0.39 , 0.06 , and $0.42 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ for RTNR, RTMR, and RTTR, respectively. Analyzing CT treatments,

only CTNR showed a positive SOC accumulation rate ($0.23 \text{ Mg C ha}^{-1} \text{ year}^{-1}$), while CTMR and CTTR exhibited SOC losses of -0.19 and $-0.62 \text{ Mg C ha}^{-1} \text{ year}^{-1}$, respectively.

The cumulative straw returned to the field for four consecutive years increased SOC stocks in both sites (Fig. 7). Straw inputs after sugarcane harvests described significant linear regression model of SOC changes (0–10 cm) under CT treatment in sandy loam soil, while under CT and RT in clayey soil ($p < 0.05$), respectively. The results suggested that about 95 kg C ha^{-1} was retained in the soil for each Mg of sugarcane straw returned in the clayey under both CT and RT treatments compared with 55 kg C ha^{-1} in the sandy under CT treatment.

Microbial biomass C and enzymatic activity

Analyzing the effects of RT system under levels of straw removal, soil biological attributes were significantly responsive in the clayey soil (0–10 cm) (Fig. 8). The magnitude of MBC and b-glucosidase activity response was directly proportional to the decrease of straw removal levels. For instance, RTTR system showed decreased MBC of 32% and 21% in comparison with RTMR and RTNR, respectively. The b-glucosidase presented the highest activity in RTNR ($45.8 \text{ mg kg}^{-1} \text{ soil}$) and RTMR ($41.3 \text{ mg kg}^{-1} \text{ soil}$) than RTTR (19.6 mg kg^{-1}).

Considering the relationship between MBC and SOC stocks, the values of MBC:SOC ratio (q_{MIC}) found in sandy loam soil showed variations between RTNR, RTMR, and RTTR treatments of 1.3, 1.8, and 1.4%, respectively, while the q_{MIC} in clayey soil decreased as a result of the increase in straw removal levels (2.9, 2.7, 2.2%) (data not shown), respectively.

Fig. 5 SOC stocks (Mg ha⁻¹) at the 0–10 and 0–40-cm soil layers under tillage systems coupled with straw removal (CTNR, CTMR, CTTR, RTNR, RTMR, RTTR) in the sandy loam and clayey soils. Data are

means from four sampling replicates. Means followed by the same letter do not indicate significant difference by Tukey test ($p < 0.05$)

Sugarcane yield

Sugarcane yield (Mg ha⁻¹) declined over the crop cycle in the sandy loam soil ($p < 0.05$) (Suppl. Table S1). There was no significant effect of tillage systems and straw removal on the average sugarcane yield in the sandy loam soil over a 5-year

period ($p > 0.05$). In the clayey soil, the yield of CTMR, CTTR, and RTTR treatments showed a substantial reduction in relation to other treatments ($p < 0.05$).

Isolating the effects of each treatment group (Fig. 9), the tillage systems did not show any changes in sugarcane yield in the sandy loam soil, but an average increase of 7 Mg ha⁻¹ was

Fig. 6 Annual rates of SOC stocks accumulation and loss (Mg ha⁻¹ year⁻¹) at soil depths of 0–10 and 0–40 cm under tillage systems

coupled with straw removal (CTNR, CTMR, CTTR, RTNR, RTMR, RTTR) in the sandy loam and clayey soils

Fig. 7 Relationship between the 4-year cumulative straw inputs (in dry basis) and SOC stocks (0–10 cm) under tillage systems (CT—

conventional tillage and RT—reduced tillage) in the sandy loam and clayey soils. $p < 0.05$ indicates linear regression is significant

observed for RT in relation to CT in clayey soil. Considering the average yield as a function of straw removal levels, no changes were also noticed in sandy loam soil. In contrast, NR treatment exhibited higher sugarcane yield in comparison with MR and TR treatments in clayey soil, with increases of 11 and 18 Mg ha⁻¹, respectively.

Discussion

Effects of tillage and straw removal on SOC stocks

Tillage practices and annual inputs of crop residues strongly influence SOC balance in agricultural areas. Sugarcane is a

crop that produces large amounts of straw per year and soil tillage generally occurs once every 5 to 6 years [14]. In most sugarcane areas, tillage operations (i.e., plowing, harrowing, and subsoiling) are still commonly used in the replanting period to alleviate soil compaction. However, due to heavy traffic of machinery, the effectiveness of these strategies for soil compaction mitigation usually has a temporary effect and requires regular recurrences [41]. In our study, the straw removal rates on SOC stocks showed different patterns when associated with tillage systems. The moderate and total removal of straw associated with the CT system resulted in a significant reduction of SOC stocks in both soils. On the other hand, the impact of straw removal rates on SOC stocks under the RT system was less detrimental in the clayey soil. These

Fig. 8 Effects of straw removal (RTNR, RTMR, RTTR) on b-glucosidase activity (black lines) and microbial biomass C (green bars) after 4 years in the sandy loam and clayey soils. Data are means from four sampling replicates. Means followed by the same uppercase letter do not indicate

significant difference of microbial biomass C and under same lowercase letter do not indicate significant difference of b-glucosidase activity by Tukey test ($p < 0.05$)

Fig. 9 Effects of tillage management systems (a) and straw removal levels (b) on the average sugarcane yield (Mg ha⁻¹) after five harvests in the sandy loam and clayey soils. Data are means from four replicates.

Datasets of the treatments used to obtain the average sugarcane yields are shown in the supplementary material (Table 1S). Means followed by same letters do not indicate significant difference by Tukey test ($p < 0.05$)

differences in SOC stocks should be associated with the impact of soil disturbance by tillage on reducing SOC stocks and thus forming a smaller SOC baseline under CT, which resulted in less SOC accumulation in areas under straw cover in the subsequent crop cycles. When fragmented, fresh residues (straw/roots/rhizomes) are incorporated in soils with nutrient shortages and available reactive binding sites are increased between soil particles and SOC; it is likely that the decomposition of protected SOC might be accelerated [42]. Depletion of SOC induced by tillage is also related to higher soil temperature and aeration, thus creating an improved environment for microbial activity and leading to reductions of the most labile C stored in both inter- and intra-aggregates [43]. However, a more stable environment under RT is maintained since less SOC is lost during the sugarcane replanting period, and consequently, a high baseline is sustained with straw additions. Other important factors influencing SOC stock under RT may be attributable to the reduction of soil temperature [44], decreasing soil microbial respiration. Moreover, RT may promote better soil conditions for soil biota and roots system and thus actively contribute to the conservation of soil particle aggregation, water and air retention/flow, and less soil erosion [19, 45].

Considering the effects of tillage systems on SOC stocks regardless of straw removal levels, the average SOC stocks found under CT decreased by 1 Mg C ha⁻¹ compared to RT in the sandy loam soil, and by 2.1 Mg C ha⁻¹ (0–10 cm layer) and 8 Mg C ha⁻¹ (0–40 cm) in the clayey, respectively (Fig. 5). Our results are aligned with other studies that observed SOC losses under CT of 3.8 Mg C ha⁻¹ relative to RT, thereby making RT a feasible strategy to reduce SOC losses [43]. Our findings indicate that a conversion from CT to NT system without straw removal would result in SOC gains of 0.31 and 0.21 Mg C ha⁻¹ year⁻¹ in the 0–10 cm for the sandy loam and clayey soils, respectively (Fig. 6). Similarly, small changes in

SOC rates were observed for the 0–40-cm layer in the sandy loam soil, but greater accumulation (1.59 Mg C ha⁻¹ year⁻¹) was observed in clayey soil. In a pioneer study in Brazil, Segnini et al. [28] isolated the effects of straw cover and tillage systems on SOC stocks in sugarcane fields. According to the authors, the adoption of CT with straw retention resulted in SOC accumulation rates of 0.67 Mg C ha⁻¹ year⁻¹, while the adoption of RT accumulated more than double (1.63 Mg C ha⁻¹ year⁻¹). Therefore, only the maintenance of sugarcane straw in the field does not guarantee significant increases in SOC stocks over time, since tillage operations during sugarcane field renovation can result in huge soil CO₂-C emissions and much of the SOC accumulated during the sugarcane cycle (plant cane and ratoons) could be lost at some weeks after tillage [25, 46].

In general, the magnitude of changes in SOC stocks depended on the cumulative amount of straw returned to the soil (Fig. 7). Considering a mean C concentration of 440 g kg⁻¹ of straw [8], the regression of cumulative straw returns against measured increases in SOC stocks suggested that about 22% of C inputs were retained in the clayey soil under both tillage systems compared with 13% in the sandy loam under CT system. Our results are similar to those reported by Robertson & Thorburn [47], who observed a C retention rate of 13% during 5 years with straw maintenance in sugarcane fields in Australia. The relationship between the increase of SOC stocks and the input of straw is well documented in the literature for sugarcane [10, 13, 14, 48, 49] and corn fields [1, 50, 51]. But, the advantages of straw maintenance on the soil go beyond of SOC accretion, given its importance in the fertility of highly weathered tropical soils, since it contributes to SOM formation, which plays an important role in improving cation exchange capacity in these soils [52]. Indirect benefits of straw cover in preserving water availability could also have contributed to soil C-input, highlighting the proper conditions

to exploration and growth of sugarcane biomass roots [53] and increased microbial biomass activity, which is one of labile C components present in the SOM [47]. Moreover, C-input from crop residues can be critical to improve soil nutrient recycling in sandy loam soils, which accumulate smaller proportions of C into the soil and are prone to losing SOC, thus favoring the preservation of a good soil functioning on a long-term basis.

The treatment RTTR showed higher SOC stocks compared with baseline. Although straw contributes to a greater biomass C-input in sugarcane fields, the effect of roots system remained from previous cycle may also have contributed to SOC accretion under the RT system [14, 54]. Additionally, considering the straw effect of the previous sugarcane cycle in these areas, it is likely that the straw previously maintained on the soil surface in the RT treatment may also have influenced C-input where all straw was removed, thus increasing SOC stocks. Aligned with these findings, predictions using modeling simulations have shown that part of SOC losses induced by straw removal can be compensated under RT as a feasible strategy in Brazil [13].

Greater SOC stocks in response to RT adoption are related to increased soil microbial activity [55]. Based on the ratio of MBC:SOC (q_{MIC}), the data provided evidences of SOC accumulation under lower levels of straw removal. This infers that higher organic C was immobilized in the microbial biomass under higher amounts of straw deposited on the soil surface (e.g., RTMR and RTNR). The maintenance of soil covered with straw under RT is likely to enhance nutrient and water availability for microbial and plant growth, which led to higher MBC content [47, 49]. Some studies reported the increase of MBC as a function of sugarcane straw retention in the field [11, 56] and under RT after cover crop [57]. It could be inferred that more labile C fraction derived of longstanding residues was biologically available to microbial respiration, which provided increasing MBC and β -glucosidase activity, thus increasing soil quality under these treatments [15, 58]. In sandy loam soil, the low β -glucosidase values reported by Lopes et al. [59] are likely related to the low SOC content as a substrate for the enzyme, which is associated to the weak interactions between sand fraction and organic C and low initial C concentrations. Similarly, the low β -glucosidase values [59] observed in clayey soil may be related to the recent intensive tillage agriculture in this area of Brazilian Cerrado (12 years with sugarcane production), which could contain complex quantity and quality of plants residues returned to soil that may have affected the degradation rate of cellulose compounds [60].

Our findings reinforce the importance of maintaining straw cover on the soil surface for the control of the labile components of SOM (microbial biomass) and SOC stocks. In this context, the combination of straw cover and RT showed to be a sustainable management strategy to mitigate SOC losses with a large potential for additional SOC sequestration.

Effects of tillage systems and straw removal on sugarcane yield

Improved sugarcane production is narrowly dependent on soil health and the adoption of sustainable management practices [61]. Several strategies have been conducted for identifying best management practices of sustainable straw removal to enhance sugarcane yield and crop longevity. The effects of tillage systems on sugarcane yields show that CT and RT over a 5-year cycle presented similar average yields in the sandy loam soil, but RT exhibited yields of $7 \text{ Mg ha}^{-1} \text{ year}^{-1}$ higher relative to CT in the clayey soil (Fig. 9). These results are very important for the context of straw management decisions for bioenergy production, since the CT system is still the main tillage used in sugarcane areas in Brazil.

In areas of high productive potential (clayey soil), the mean yield under CTTR and CTMR ($\sim 8 \text{ Mg ha}^{-1}$) considerably reduced sugarcane yield. The maintenance of straw on the soil surface in the clayey soil was crucial to sustaining high sugarcane yields levels by preserving soil moisture, especially at an early stage of the crop growth, in which drought conditions are observed during the four ratoon cycles (Fig. 2). Other studies have demonstrated that straw retention increases sugarcane yield [10, 61] which may be attributed to the improvements of soil quality [16, 62]. Low sugarcane yields under high removal of sugarcane straw are explained by the impaired capacity of ratoons to regrowth and uptake water/nutrients after harvest [63]. The soil covered with straw recycles nutrients from the previous cycle to the growing plant and is likely to reduce soil erosion, water runoff/evaporation, which increases the water use efficiency in the superficial layers [18] where the most quantity of sugarcane roots is confined [64, 65]. Although the mean yield under RTTR was higher than CTMR and CTNR, this management strategy may not guarantee that best soil functions will be preserved without the long-term benefits of straw retention.

In this study, sugarcane yield in sandy loam soil was not responsive to the straw removal levels (Fig. 8), which could be related to its condition of better aeration, high-water infiltration and low fertility that may have not favored crop production. But a concern regarding straw removal under this soil type conditions is the cover protection that diminishes the potential for soil erosion losses [12]. The presence of straw on soil surface along the year may be useful in this area for other reasons such as regulating soil temperature variations, maintaining soil physical conditions, fauna/microbial activities, nutrient cycling, and SOC, which may reflect in yield gains [5, 9]. A significant yield decline along the crop cycle was observed in sandy loam area (Suppl. Table 1), which may be associated to the natural decline of productive capacity of sugarcane ratoons and damages in the stool caused by heavy mechanized traffic [66].

Implications of tillage systems and straw removal in sugarcane sector

Opinions about the straw removal recommendations are based on diverse arguments, including edaphoclimatic conditions and management practices [5]. As important as assessing the amount of sugarcane straw on soil surface, considering tillage systems were also critical to fully account for management-induced changes on SOC stocks and sugarcane yields for industrial uses. Our findings endorse the importance of adopting a sugarcane system based on reduced tillage combined with sustainable straw management strategies for enhancing SOC stocks while still improving or not compromising sugarcane yields. The CT system is currently performed during sugarcane planting to attenuate soil compaction as an immediate solution, but if CT does not justify in terms of yield gains or even prevent SOC losses, why should it be implemented? Significant reductions in SOC stocks and sugarcane yields tended to be clearly site-specific under CT combined with moderate and total straw removal (Figs. 5 and 9). However, while inappropriate management practices may deplete soil C stocks, adoption of best management practices that reduce soil C losses are key opportunities to further enhance the C savings of Brazilian sugarcane ethanol production in areas under straw removal [13]. The benefits of straw retention may also be important in view of the sugarcane expansion in the Brazilian Cerrado region, where more restrictive environments are usually common in terms of soil fertility and climatic conditions. Special attention should be given for sandy soils, in which RT and avoidance of sugarcane straw removal are crucial issues to maintaining SOC stocks. Additionally, concerns regarding the environmental costs with fuel and tractor hours during sugarcane planting under CT system have not been approached in this study, but the RT adoption as an alternative to CT reduces diesel consumption by avoiding some tillage operations and, consequently, could provide a 22.7% reduction of GHG balance of sugarcane production [67].

Our findings support the idea that sugarcane systems with straw removal should consider potential RT effect on SOC accumulation to meet reduction of Brazilian GHG emissions target. If we consider that the best scenario for potential SOC accumulation was RTNR in both soils (0–40 cm), the conversion of sugarcane areas from a traditional scenario in Brazil under CTNR to RTNR system could provide a mean net SOC accumulation of $0.9 \text{ Mg ha}^{-1} \text{ year}^{-1}$ (difference in SOC stocks between CTNR and RTNR). Assuming that most of the sugarcane cultivated areas in Brazil (9 million ha) is currently cultivated under CTNR system, the adoption of a RTNR system could result in additional SOC accumulation of $8.1 \text{ Tg C year}^{-1}$ into the soil, which corresponds to a soil C sequestration capacity of $29.73 \text{ Tg CO}_2 \text{ year}^{-1}$ from the atmosphere. Therefore, the adoption of RT would mean offsetting part of

the total GHG emissions associated with Brazilian agricultural activities in sugarcane areas. An effective strategic plan for implementing RT system with a sustainable straw removal would represent a relevant contribution to achieve the ambitious targets of reducing GHG emissions by 37% in 2025 announced by the Brazilian government in the last Paris climate agreement within the United Nations Framework Convention on Climate Change (COP21).

Future studies should focus on management practices to maximize the quality of the RT system to improve SOC conservation under straw removal scenarios. Considering that RT performed in sugarcane fields represents a considerable soil disturbance in the crop row of 12.5% of the surface layer (Fig. 1) for opening the planting furrows in comparison with grain crops, studies should focus on improving technology that reduces soil disaggregation during sugarcane planting by adopting, for example, planting of sugarcane pre-sprout systems [68]. Other important practices include the use of rotation with leguminous crops, controlled traffic farming, double crop row spacing, and adjustments of machines width. The recent study demonstrates longer sugarcane longevity when the combination of procedures is implemented in conjunction with accurate guidance of machine traffic in the field, which will preserve the physical quality of the crop row and enhance cane yields [69]. Therefore, the adoption of RT could provide a moderate straw removal for bioenergy production with SOC storage sustenance and potentially extra revenue by increasing stalk yield and saving agricultural inputs (e.g., fertilizers and fuels).

Conclusions

Can RT be a feasible strategy to “prevent” SOC loss induced by straw removal while sustaining sugarcane yields? Conclusions drawn from this study suggest that RT system with a moderate straw cover in the soil could potentially provide sustainable use of parts of the straw from the field for bioenergy purposes while enhancing SOC stocks and sustain sugarcane yields over the crop cycle in both soils. The adoption of RT could be a management strategy to offset the adverse effects of straw removal in the sugarcane sector. The microbial indicators in the clayey soil point out to increases in SOC turnover under RT with moderate and no straw removal, which could lead to an increase in SOC stocks. The straw removal in areas under CT system intensifies SOC losses and does not reflect in higher sugarcane yield compared to RT. In clayey soil, CT system combined with moderate and total removal of straw showed SOC losses (0–40 cm) at a rate of 0.18 and $0.50 \text{ Mg ha}^{-1} \text{ year}^{-1}$, respectively. Similarly, SOC losses in sandy loam soil under CTTR reached up to $0.62 \text{ Mg ha}^{-1} \text{ year}^{-1}$ and SOC accumulation ($0.23 \text{ Mg ha}^{-1} \text{ year}^{-1}$) was observed only when all the straw was left on the soil surface.

Sugarcane yield was not affected by tillage systems in the sandy loam soil, but CT under total and moderate removal of straw decreased cane yields in clayey soil.

Based on the mid-term empirical data, these findings highlight the need to decrease soil disturbance in traditional CT, suggesting RT as a feasible tillage strategy for more sustainable sugarcane production. We advocate that additional modeling efforts on long-term SOC dynamics are needed to validate these findings to credibly assess the longstanding impacts to make a safer and accurate decision about the magnitude and levels at which straw can be sustainably removed.

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Compliance with ethical standards

Conflict of Interest The authors declare that they have no conflict of interest.

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