INTRODUCTION

Soil organic carbon (SOC) plays a crucial role for mitigating global climate change (FAO, 2019; IPCC, 2019). However, the intensification of tillage and other crop production practices (e.g., monocropping), when poorly managed, have led to serious soil degradation and the release of carbon to the atmosphere (Sanderman et al., 2017). Recognizing the soil...
reservoir can potentially store three times as much C as in the atmosphere (Lal, 2004; Sanderman et al., 2017), actions have been proposed to rebuild SOC stocks by applying good soil and crop management strategies (Vermeulen et al., 2019). Soils that are poorly managed can increase CO₂-C emissions, whereas sustainably managed soils can sequester C, reduce global warming (FAO, 2019; IPCC, 2019), and enhance soil-related ecosystem services (Lorenz et al., 2019).

Globally, sugarcane stands out as a crop with significant potential to minimize the agricultural C footprint. Sugarcane-derived bioethanol is one of the most promising renewable energy alternatives to petroleum-based transport fuels and, is recognized for its potential ability to emit less life cycle C and avoid negative impacts on food security and biodiversity (Bordonal, Carvalho, et al., 2018). Brazil is the largest world sugarcane producer, with 8.6 million hectares of estimated cultivated area and production of 29.8 billion L of bioethanol (Conab, 2020). In recent decades, sustainability concerns regarding sugarcane cultivation with pre-harvest burning led to major changes in Brazilian crop harvesting practices, such that green, mechanized harvest systems have been adopted. This new harvest approach leaves a thick layer of straw (10–20 Mg/ha) on the soil surface, thus providing several agro-environmental benefits including SOC accretion, microbiota support, nutrient cycling and improved soil structure (Carvalho, Nogueiro et al., 2017; Cerri et al., 2011).

The sugarcane industry has recently shown increased interest in removing straw for bioenergy production because of several sectoral policies such as the Renovabio program driven by international commitments under the Paris Convention of the Parties (COP 21) to identify potential renewable substitutes for fossil fuels (IPCC, 2019). However, several recent studies have confirmed that excessive removal of agricultural residues can lead to SOC depletion (Alam et al., 2019; Battaglia et al., 2020; Berhane et al., 2020; Bordonal, Carvalho, et al., 2018; Bordonal, Menandro, et al., 2018; Cherubin et al., 2019; Xu et al., 2019). In particular, special attention should be given to straw removal from coarse-textured soils, since those soils are usually less resilient to SOC losses (Bordonal, Menandro, et al., 2018). Dieckow et al. (2009) verified that a strong interaction between clay fraction and SOC exists, since clay particles tend to form aggregates that physically protect SOC against microbial and enzymatic attack. However, there is a lack of comprehensive studies evaluating the effects of straw removal on SOC stocks in different soil types and climate conditions in Brazil needed to provide a reliable scientific basis for public policies and management decisions.

Based on this context, we hypothesized that (a) indiscriminate rates of straw removal intensify SOC stocks depletion, and (b) the removal of sugarcane straw is more deleterious to SOC stocks in sandy than in clay soils. To test these hypotheses, we conducted a set of 10 field experiments to evaluate the temporal alterations of SOC stocks in sugarcane fields under straw removal across contrasting soil textural classes in south-central Brazil, the main sugarcane-producing region in the country. Specific goals were to determine SOC responses to straw removal rates and quantify the minimum amount of straw required to sustain the SOC levels for sandy and clay soils.

2 MATERIAL AND METHODS

2.1 Description of the study areas

Ten field experiments were located at states of São Paulo and Goiás, which are the two largest sugarcane-producing areas in south-central region of Brazil (Figure 1). The trials were carried out on different soil types and conducted...
within commercial sugarcane production areas without disrupting the standard crop cycle. Eight of 10 sites were classified as sandy or clay soils, with sites 6 and 7 classified as having a loam texture. To simplify data analysis, the sites were grouped into two classes (sandy or clay) and sites 6 (23% clay) and 7 (33% clay) were included with sandy and clay texture sites, respectively. Descriptions of experimental sites and soil physicochemical attributes during the experimental setup are presented in Tables 1 and 2.

2.2 Experimental design and treatments

Each one of the 10 field trials were arranged in a randomized block design with four replications. The plots were 10-m long and 12-m wide with eight sugarcane rows spaced 1.5 m apart. Straw management treatments were established following plant cane cycle harvest, which is when straw is available for harvest in sugarcane fields. The quantity of straw produced at each site was quantified by randomly throwing a metallic frame (0.25 m²) to 10 locations within each plot and collecting the surface residue. Straw moisture was measured using an AL-104 Agrologic® sensor coupled to an E-831 electrode. After quantifying the amount of available straw dry mass, removal treatments were imposed manually using rakes and forks during each year or ratoon phase. At seven sites, four removal rates were established (total–TR, high–HR, low–LR and none–NR). Removal rates at the other three sites were based on the amount of straw produced each year and classified as 0%, 50%, and 100% removal. Since the sites had different rates of straw removal, treatments were grouped for statistical analysis as follows: NR (all straw left on soil surface), LR (from 25 to 33% removal), HR (from 50 to 66% removal) and TR (no straw on the soil – bare soil). Actual quantities of straw left on the soil surface for each site, treatment, and year are presented in Table 3.

All 10 field experiments were fertilized with 120 kg/ha N (ammonium nitrate) and 120 kg/ha K₂O (potassium chloride). No organic amendments (i.e., filter cake or vinasse) were applied. Fungicide, herbicide, and insecticide applications were made uniformly following routine practices determined by each sugarcane mill. Prior to experimental period, during sugarcane planting all sites were subjected to conventional tillage practices (subsoiling and harrowing) and no tillage operations were performed during the experimental period (Figure 2).

2.3 Soil sampling and measurements

Baseline SOC was quantified before straw management at each site, with follow-up measurements after 2 (Sites 1, 5, 6, and 7) or 4 years of straw removal (Sites 2, 3, 4, 8, 9, and 10). Composite soil samples were collected at each plot from within and between rows for depth increments of 0–5, 5–10, 10–20, and 20–30 cm. The samples were air-dried at 35°C for 7 days, then after gentle grinding, they were passed through a 2-mm sieve. A 10-g subsample was finely ground to pass through a 0.150-mm sieve before measuring total C concentration (in duplicate) using the dry combustion method with a LECO CN 628 Carbon Analyzer (Nelson & Sommers, 1996). To quantify soil C stocks, bulk density (BD) was determined by collecting an undisturbed sample from the middle of each depth increment using volumetric rings (5-cm internal diameter and 5-cm high). Each core sample was weighed before and after oven drying at 105°C. The dry weight was then divided by the cylinder volume to compute BD (Mg/m³) as outlined by Blake and Hartge (1986).

2.4 Calculation of SOC stocks and annual rates of SOC loss/accumulation

SOC stocks were calculated for all soil depths (0–5, 5–10, 10–20, and 20–30 cm) according to Equation 1:

\[
\text{SOC}_{\text{stocks}} = \text{C content} \times \text{bulk density} \times \text{soil layer}
\]

where, SOC stocks (Mg/ha) was obtained by multiplying soil C content (%) by bulk density (Mg/m³) and soil layer (cm). Additionally, the stocks of each sampled depth were counted to estimate the SOC stocks for the 0–10- and 0–30-cm layers. Because soil samples were collected from fixed layers, the SOC stock was adjusted for changes in bulk density that occurred after soil management. For this, SOC stocks were adjusted to an equivalent soil mass using as reference the comparison with the baseline characterization (before straw removal treatments) of each experimental site according to methodology of Ellert and Bettany (1995).

Losses and accumulations of SOC (Mg ha⁻¹ year⁻¹) in each experimental site were computed for the 0–30-cm layer according to Equation 2 to represent changes in SOC stocks induced by the removal rates relative to baseline SOC stock.

\[
\text{SOC}_{\text{loss/accumulation}} = \frac{\text{SOC}_{\text{stockfinal}} - \text{SOC}_{\text{stockinitial}}}{\text{years}}
\]

in which, SOC loss/accumulation is the annual rate of C loss or accumulation (Mg ha⁻¹ year⁻¹) for the treatments of straw removal in each site; SOC stockfinal is the C stock (Mg/ha) related to each straw removal treatment at the end of the experimental period; SOC stockinitial is the referential C stock (Mg/ha) before the treatment establishment (baseline); and years is the experimental period.

Regression models using the relationship between ∆SOC (SOCfinal − SOCinitial) as a function of sugarcane straw biomass
### TABLE 1 Descriptions of the research sites

| Soil type | Sandy soils | Clay soils |
|-----------|-------------|------------|
| Municipality Units | Itirapina/SP (Site 1) | Quatá/SP (Site 2) | Quatá/SP (Site 3) | Valparaíso/SP (Site 4) | Quirinópolis/GO (Site 5) | Capivari/SP (Site 7) | Quirinópolis/GO (Site 8) | Iracemápolis/GO (Site 9) | Chapadão do Céu/GO (Site 10) |
| Latitude/Longitude | 22°15′44″S, 47°46′45″W | 22°19′52″S, 50°38′05″W | 22°12′49″S, 50°02′27″W | 21°14′48″S, 50°38′25″W | 18°46′44″S, 50°38′46″W | 22°59′42″S, 47°30′34″W | 18°33′24″S, 50°25′04″W | 22°36′03″S, 47°34′31″W | 18°27′55″S, 52°34′60″W |
| Soil classification | Typic Quartzipsammets | Arenic Kandiudult | Arenic Kandiudult | Arenic Kandiudult | Kanhaplic Haplustults | Typic Kandiudox | Rhodic Kandiudox | Rhodic Eutrudox | Rhodic Eutrudox | Rhodic Hapludox |
| Altitude m | 830 | 541 | 518 | 541 | 405 | 480 | 536 | 460 | 613 | 799 |
| MAR mm | 1,367 | 1,254 | 1,254 | 1,254 | 1,168 | 1,52 | 1,188 | 1,52 | 1,294 | 1,627 |
| Tmean °C | 19.6 | 20.8 | 20.8 | 20.8 | 21.9 | 22.5 | 20.3 | 22.5 | 20.4 | 21.1 |
| Climate | C1wB′4a | C1wA′a | C1wA′a | C1wA′a | B1wA′a | C1wB′4a | B1wA′a | B1wB′4a | B1wA′a |
| Crop variety | CT96-3346 | RB867515 | RB966928 | RB966928 | RB867515 | RB966928 | CTC14 | RB966928 | IACSP95-5000 | RB966928 |
| Evaluation period years | 2 | 4 | 4 | 4 | 2 | 2 | 2 | 4 | 4 | 4 |
| Previous land use | Pasture | Pasture | Pasture | Pasture | Pasture | Pasture | Pasture | Pasture | Pasture | Pasture |
| Conversion to sugarcane | 2005 | 2012 | 2008 | 1995 | 1997 | 2006 | 1977 | 2006 | 1970 | 2007 |
| Adoption of burned harvesting | 2005–2009 | - | - | 1995–2009 | 1997–2009 | - | 1977–2007 | - | 1970–2008 | - |
| Adoption of green harvesting system | 2009 | 2012 | 2008 | 2009 | 2009 | 2006 | 2007 | 2006 | 2008 | 2007 |

MAR, mean annual rainfall; Tmean, mean annual temperature; Altitude above sea level.

*aUSDA-Soil Taxonomy (Soil Survey Staff, 2014).

*bThornthwaite (1948).
| Soil type | Sandy soils | Clay soils |
|-----------|------------|------------|
| **Municipality** | **Units** | **Itirapina/SP (Site 1)** | **Quatá/SP (Site 2)** | **Quatá/SP (Site 3)** | **Quatá/SP (Site 4)** | **Valparaíso/SP (Site 5)** | **Quirinópolis/GO (Site 6)** | **Capivari/SP (Site 7)** | **Quirinópolis/GO (Site 8)** | **Iracemápolis/GO (Site 9)** | **Chapadão do Céu/GO (Site 10)** |
| pH CaCl$_2$ | | 5.5 | 5.0 | 5.4 | 4.8 | 4.8 | 5.9 | 4.8 | 5.5 | 5.2 | 5 |
| SOC | g/kg | 6.1 | 5 | 4.9 | 4.2 | 5.7 | 9.3 | 11.2 | 17.9 | 17.1 | 21.6 |
| P | Mg/kg | 38 | 9 | 7 | 16 | 15 | 5 | 25 | 11 | 46 | 11 |
| K | mmolc dm$^{-3}$ | 1.5 | 1.0 | 1 | 0.3 | 2.7 | 0.6 | 5.9 | 4 | 10.6 | 2 |
| Ca | | 17 | 18 | 34 | 12 | 6 | 17 | 19 | 40 | 54 | 26 |
| Mg | | 9 | 7 | 3 | 4 | 2 | 8 | 5 | 12 | 29 | 9 |
| BS | % | 54 | 61 | 79 | 49 | 38 | 61 | 53 | 71 | 65 | 53 |
| BD | Mg/m$^3$ | 1.64 | 1.75 | 1.68 | 1.7 | 1.57 | 1.77 | 1.33 | 1.3 | 1.38 | 1.16 |
| Sand$^b$ | g/kg | 923 | 807 | 825 | 829 | 863 | 749 | 603 | 247 | 229 | 209 |
| Clay | | 54 | 72 | 111 | 112 | 115 | 226 | 330 | 563 | 602 | 639 |
| Silt | | 22 | 122 | 64 | 59 | 22 | 25 | 65 | 190 | 168 | 152 |

SOC, soil organic carbon; BS, base saturation; BD, bulk density.

$^a$Soil chemical analysis according to Van Raij et al. (2001).

$^b$Soil particle-size analysis according to Blake and Hartge (1986).
inputs were performed to estimate the minimum amount of straw (Mg ha⁻¹ year⁻¹) needed to sustain SOC losses (when y = 0). For the sites 7, 8, and 10, the relationship between ∆SOC and accumulated C inputs was not significant, and therefore, the minimum quantity of straw to sustain SOC stock could not be determined. For sandy soils (sites 3, 4, 6), where negative slopes with positive corresponding x-intercept were found, the minimum quantity of straw was much higher than the productive potential capacity of these sites and, consequently, it was not possible to approximate a realistic minimum quantity of sugarcane straw required to maintain SOC stock.

2.5 Data analysis

Statistical analysis of data from each site was done considering the design of randomized blocks, and analysis of variance (ANOVA) was used to investigate the alterations in SOC stocks driven by straw removal. Data normality was confirmed by the Shapiro–Wilk test at 5% significance, and data transformations were not necessary to meet ANOVA assumptions. When statistically significant (F test; p < 0.05), the average values of SOC stocks were compared between treatments by Tukey’s test (p < 0.05) and by Dunnett’s test (p < 0.05) for comparison with baseline. Regression analyzes were also done to investigate the relationships between SOC stock changes and cumulative straw inputs for consecutive years. All statistical analyses were performed using R software (R Development Core Team, 2019).

3 RESULTS

3.1 SOC changes driven by straw removal

Overall, straw removal induced significant SOC stock depletions and the effects were more evident in the topsoil (0–10 cm) for sites 1, 2, 4, 8, and 9 (Figure 3). Sandy soils were severely susceptible to SOC losses induced by straw removal. In site 1, TR treatment (10.6 Mg/ha) depleted SOC stocks by 18% in the 0–10 cm soil layer compared to all straw on the soil surface (13 Mg/ha) but did not differ from LR and HR treatments. After four consecutive years of straw removal, the effects were even more intense in site 2, where LR, HR and TR depleted SOC stocks (0–10 cm) from 18 to 48% compared to maintaining soil cover with straw (NR). Similarly, HR and TR treatments in site 4 reduced SOC stocks from 6% to 21% in comparison

| TABLE 3 | Amount of straw maintained (Mg/ha of dry basis) on soil surface based on the straw removal rate established in percentage of total straw production |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Sites 1*, 2, 3, 6*, 9 | Straw removal rate | Amount of straw left on soil surface (Mg/ha) | 1st year | 2nd year | 3rd year | 4th year |
| | TR | 0 | 0 | 0 | 0 |
| | HR | 5 | 5 | 5 | 5 |
| | LR | 10 | 10 | 10 | 10 |
| | NR | 15 | 15 | 15 | 15 |
| 4 | TR | 0 | 0 | 0 | 0 |
| | HR | 4.6 | 6.3 | 3.8 | 3.8 |
| | NR | 9.2 | 12.6 | 7.5 | 7.5 |
| 5* | TR | 0 | 0 | - | - |
| | HR | 5.1 | 4.1 | - | - |
| | LR | 11.4 | 9.6 | - | - |
| | NR | 15.0 | 12.4 | - | - |
| 7* | TR | 0 | 0 | - | - |
| | HR | 3.4 | 3.2 | - | - |
| | LR | 13.0 | 11.4 | - | - |
| | NR | 16.6 | 14.7 | - | - |
| 8 | TR | 0 | 0 | 0 | 0 |
| | HR | 8.3 | 8.6 | 8.6 | 6.7 |
| | NR | 16.5 | 17.2 | 17.2 | 13.4 |
| 10 | TR | 0 | 0 | 0 | 0 |
| | HR | 7.5 | 8.0 | 7.4 | 5.0 |
| | NR | 14.9 | 15.9 | 14.7 | 10.0 |

NR, HR, and TR denote no, high and total straw removal rates, respectively. Asterisk (*) symbol on the respective site indicates that straw management was performed up to the second year.

FIGURE 2 Timeline of management practices adopted during the experimental period
with NR. In the 0–30-cm layer, sites 2 and 4 presented SOC reductions from 16 to 29% only for TR relative to NR treatment. Considering only the sandy soils (sites 2 and 4) where differences between treatments were significant in 0–30 cm, the data show that the mean of straw removal treatments resulted in SOC losses ranging from 0.2 to 0.9 Mg ha$^{-1}$ year$^{-1}$ compared to NR.

Similarly, straw removal affected SOC stocks in clay soils (sites 8 and 9), where SOC depletions were directly proportional to the increase in straw removal rates in the 0–10-cm layer (Figure 3). In site 8, decreases in SOC stock (13%) was observed in the TR (31.0 Mg/ha) compared to NR (35.7 Mg/ha). In site 9, the HR (27.2 Mg/ha) and TR (26.8 Mg/ha) treatments reduced SOC stocks in the 0–10 cm compared to NR (32.3 Mg/ha), whereas SOC depletion in the 0–30 cm was up to 11% with the complete removal of straw (66 Mg/ha) relative to NR treatment (73.9 Mg/ha).
Comparing the final SOC stocks with the referential SOC stock for each site, both soil types showed greater SOC losses with increase in the removal rates of sugarcane straw. However, in sandy soils, SOC stocks tended to decrease over time regardless of the straw removal rate (Figure 4 and Table S1), thus indicating a SOC loss during the sugarcane crop cycles. On average, the reduction of SOC stocks in the 30-cm depth in sandy soils compared with baseline varied at rates of 2.3, 1.9, 1.5, and 1.4 Mg ha⁻¹ year⁻¹ for the TR, HR, LR, and NR, respectively. The results revealed that SOC stocks were reduced over time even with all straw maintained on the soil surface (NR). Conversely on clay soils, no significant changes on straw removal treatments compared to initial period of the trial were observed in all sites (Figure 4).

3.2 | Relationship between cumulative straw inputs and SOC stocks

Even though SOC stocks have decreased during the period evaluated under sandy soils, our results revealed that sugarcane straw is playing its role in adding C for the treatments. It was observed that cumulative increase in the amount of straw added to the soil promoted increase in SOC stocks over the evaluated period (Figure 5). On average, the data show that 85 kg C/ha was retained in sandy soils for each megagram (Mg) of straw left in the field, and the data ranged from 26 to 144 kg C/ha. Clay soils showed average C retention of 109 kg C/ha for each Mg of dry matter straw in the field, varying from 91 to 134 kg C/ha. Only in three out of ten evaluated sites was possible to quantify the minimum amount of straw biomass on soil surface required to maintain SOC stocks based on linear regression (to find the X value, we considered y = 0) (Figure S1). The change in ∆SOC as a function of straw biomass inputs showed an estimated quantity of straw return necessary to sustain SOC stocks of 16, 12, and 8 Mg ha⁻¹ year⁻¹ for sites 1, 2, and 9, respectively.

4 | DISCUSSION

4.1 | SOC storage under different soil types in sugarcane fields

Understanding the effects of different soil textures on SOC storage is essential for providing the scientific basis for public and sectorial policy discussions regarding sustainability of bioenergy production systems. Experimental evidence from this study showed a strong influence of soil texture on SOC changes over time. Regardless of straw management, the data clearly showed that coarse-textured soils were highly susceptible to SOC reduction, showing a mean loss rate of 1.8 Mg C ha⁻¹ year⁻¹. This indicates that there were SOC stocks reduction in sandy soils compared with the period before straw management (baseline), which means that the soil is not sustaining SOC stocks (Figure 4). Conversely, in clay soils, SOC stocks were similar between baseline and all treatments of straw removal.

Studies under tropical and subtropical conditions have reported that fine-textured soils are less susceptible to SOC losses in cropping systems (Dieckow et al., 2009). This pattern can be attributed to the mechanisms that govern the stability of SOC, such as the high sorption capacity of mineral surfaces in clay soils. The strong interactions with clay fractions stabilize organic-C compounds, preserving them...
against decomposition (Dignac et al., 2017; Kopittke et al., 2020; Spohn, 2020). Likewise, greater specific surface area of clay particles and more complex pores network increase aggregate protected C substrates by physical inaccessibility to degradation (Kravchenko et al., 2019). The organo-mineral interactions between C compounds and sand fractions are recognized as weak (Dieckow et al., 2009; Neufeldt et al., 2002), which may explain the significant SOC losses induced by sugarcane production in sandy soils. Our results show that in the most representative scenario of sugarcane production in south-central Brazil, based on green mechanized harvesting (all straw maintained in the field), monoculture and conventional tillage on replanting period, could not sustain SOC stocks in sandy soils.

In addition to the fact that the lower SOC stocks in sandy soils are related to textural properties, this may also be associated with sugarcane productive potential of these areas. For example, Carvalho et al. (2019) measured sugarcane yields in the same experimental areas and concluded that sandy soils produce 40% less biomass and crop residues than clay soils. The authors reported that the higher yields in clay soils are linked to greater water availability and soil fertility, thus providing proper conditions for root growth and development. Since roots and exudates are important inputs of C to the soil in sugarcane areas (Carvalho et al., 2013), the contribution of root compartments to SOC stocks is likely to be lower in sandy than clay soils.

It is also important to acknowledge that conventional tillage was carried out during sugarcane renovation (before straw management establishment) and this effect should be deleterious to SOC stocks along the crop cycle. Intensive soil tillage exposes SOC that is protected by aggregates and make it available for microbial use, thus causing SOC losses by inducing CO₂ emissions releases to the atmosphere (La Scala et al., 2006; Silva-Olaya et al., 2013). Similarly, Segnini et al. (2013) stated that most part of the SOC accumulated along the sugarcane cycles could be lost in the renovation period under conventional tillage, and Cerri et al. (2011) mentioned that such C losses are high in sandy soils. Conversely, many studies have suggested that the adoption of reduced tillage could be a feasible strategy to avoid not only SOC losses during the renovation periods (Segnini et al., 2013; Tenelli et al., 2019), but also to increase the capacity of sugarcane soils to accumulate C over time. Alternative strategies to avoid SOC depletion in sugarcane fields includes implementation of crop rotation, maintenance of the soil surface covered with straw and application of organic amendments such as filter cake, vinasse, and biochar (Bordonal, Menandro, et al., 2018).

To avoid SOC loss, it is important to consider soil type when implementing specific management practices. For example, in clay soils, SOC were maintained throughout the cropping cycle, but in sandy soils, significant losses were observed. The results also document how challenging it is to sustainably integrate sandy soils (marginal lands) into productive bioenergy production systems, especially in tropical climate regions. Therefore, it is imperative that additional studies be conducted to help establish guidelines for sugarcane production on sandy soils that will ultimately reduce SOC losses over time.

4.2 Implications of sugarcane straw removal on SOC stocks

Sugarcane-based biofuels can provide viable solutions for reducing dependence on fossil fuels, ensuring energy security, and mitigating greenhouse gas (GHG) emissions compared to other energy crops such as maize and sugar beet (Goldemberg & Guardabassi, 2010). However, it is not clear if the effects of crop residue removal on SOC stocks can be offset by avoided GHG emissions of sugarcane-based bioenergy production (e.g., cellulosic ethanol or electricity) when substituted for fossil fuel sources.

By combining information from 10 experimental sites representing the main sugarcane producing regions in Brazil (i.e., 90% of the country’s production and 36% of the global supply), this study provides a comprehensive dataset regarding SOC stock changes driven by straw removal under different soil textures. Overall, SOC stocks were reduced at most experimental sites, with general depletion as removal rates increased (HR and TR). These results are also consistent with prior long-term predictions from modelling research in Brazil (Carvalho, Hudiburg, et al., 2017; Oliveira et al., 2017), and are in line with SOC declines reported for corn (Zea mays L.) stover removal around the world (Battaglia et al., 2020; Berhane et al., 2020; Johnson et al., 2014; Xu et al., 2019). Aligned with our findings, recent studies have shown that the maintenance of sugarcane straw on soil surface supports several soil ecosystem services, including decreasing soil erosion (Carvalho, Nogueiro, et al., 2017), creating more favorable environments for microbiological processes (Pimentel et al., 2019; Tenelli et al., 2019), stabilizing soil aggregates (Castioni et al., 2019), enhancing nutrient cycling and reducing fertilizer consumption (Cherubin et al., 2019), all which have an essential role in boosting sugarcane yield (Carvalho et al., 2009). By the way, what was the role of straw for each removal treatment? Considering the quantity of C added by sugarcane straw, we examined the impact of removal for each treatment regarding how much C was retained and incorporated into soil organic matter. Assuming sugarcane straw has 440 g/kg of C in the dry matter (Menandro et al., 2017), our results suggested that 19% and 25% of the C added via straw was retained into the soil in sandy and clay soils, respectively. These values are higher than those found in the literature for sugarcane and other crop residues,
which usually ranges from 6 to 15% (Bolinder et al., 1999; Robertson & Thorburn, 2007; Sousa Junior et al., 2018). For example, Robertson and Thorburn (2007) observed that 13% of C input via sugarcane straw was accumulated in the soil after 5 years of straw maintenance in Australian conditions.

Based on regression equations between cumulative straw C input and SOC, clay soils required 8.1 Mg ha\(^{-1}\) year\(^{-1}\) of straw to sustain SOC stocks, while 11.0–16.3 Mg ha\(^{-1}\) year\(^{-1}\) were necessary for sandy soils. However, only one clay site and two sandy sites showed a linear relationship between ΔSOC and straw additions (Figure S1). In contrast to this study, Johnson et al. (2014) observed a minimum corn stover amount of 6.38 Mg ha\(^{-1}\) yr\(^{-1}\) necessary to maintain SOC stocks in the soils of Corn Belt, USA, where the soil was described to be close to C saturation. However, the conceptual approach for estimating SOC changes used by Johnson et al. (2014) did not work well for this study. For instance, the y-intercept for each regression equation was consistently greater than zero in clay soils, meaning that SOC stocks were maintained even with complete straw removal. The lack of a negative effect of straw removal from clay soils can be attributed to other C sources (e.g., roots, exudates), that may have been sufficient to sustain SOC stocks by keeping the carbon protected by interactions with clay particles (Dignac et al., 2017). In sandy soils, the absence of response is likely related to the low capacity of these soils to accumulate C, showing that the minimum quantity of sugarcane straw to sustain SOC was so high and far away from what those areas could potentially produce because of their limited conditions.

This study highlights that straw-derived bioenergy is not “zero impact” in terms of C budget, since it directly affects soil C stocks. Regardless of whether SOC stocks were not affected (clay soils) or decreased (sandy soils) in comparison with baseline as previously discussed in Section 4.1, our findings confirm the role of sugarcane straw as a primary soil C source and indicates that removal has the tendency to reduce SOC stocks. Therefore, to ensure bioenergy production is environmentally sustainable, benefits of biofuels produced from crop residues must compensate for potential SOC losses.

Since sandy soils are more vulnerable and present challenges for accumulating or even maintaining SOC stocks, this study raises the following question: Can sandy areas really support straw removal? We conclude that removal from those areas would not be sustainable with current soil and crop management practices. However, large-scale expansion of sugarcane production on sandy soils has primarily occurred during the past 15 years in south-central Brazil. As a result, SOC stocks changes due to crop residues removal are poorly understood, and improved management practices need to be developed through additional comprehensive studies.

Overall, this study shows that the straw retention is crucial to reduce SOC losses in sugarcane systems especially for sandy soils managed with conventional tillage, and alternative management practices including use of no tillage, crop rotations and organic amendments could offer climate-smart solutions to ensure food security and sustain soil productivity (Alam et al., 2019; McNunn et al., 2020; Yang et al., 2019; Zhao et al., 2020). For example, Tenelli et al. (2019) concluded that the implementation of reduced tillage offsets part of SOC losses caused by straw removal, and consequently, greater amount of sugarcane straw can be rationally removed from the fields without depleting SOC stocks. Changes in SOC stock are driven by a variety of processes that are interconnected, and therefore, determining how much straw is needed to maintain SOC stock levels for a sustainable bioenergy production using short- and medium-term empirical data is still challenging. The establishment of critical levels of straw removal at site/farm or regional scale should vary according to the site specificity of soil, climate and management strategies. Therefore, to estimate the influence of each factor on SOC stocks, simulation models can be a useful approach to assess critical levels of straw mulching and predict these long-term impacts on SOC dynamics. Finally, we advocate inclusion of SOC stocks changes in life-cycle assessments. This should be mandatory and encouraged for both sandy and clay soils for the most credible GHG balance of sugarcane straw-derived bioenergy.

5 | CONCLUSIONS

Crop residue-based bioenergy feedstock production appropriately raises concerns regarding indiscriminate straw removal rates on SOC stocks and sustainability of sugarcane production system. This study confirms that sugarcane straw is an important input of C to the soil and the excessive rates of straw removal are impacting SOC stocks. This suggests that rational straw management must be adopted to prevent additional soil degradation. Our findings also showed strong SOC depletion in sandy soils regardless of the quantities of straw maintained on soil surface.

Finally, production of sugarcane-derived ethanol, energy and other biorenewables in Brazil from crop residues may be advantageous from an energy security point of view, but it should be avoided in areas of sandy soils because it reduces SOC from a naturally infertile soil. Decision regarding sugarcane straw removal rates should consider information on soil type, tillage practices and other management strategies that can affect SOC stocks. Therefore, we advocate that the use of crop residues for bioenergy production in Brazil should not deplete SOC stocks, especially since tropical soils are characterized by low SOC levels and favorable environments for fast SOC loss due to decomposition.

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REFERENCES

Alam, M. K., Bell, R. W., & Biswas, W. K. (2019). Increases in soil sequestered carbon under conservation agriculture cropping decrease the estimated greenhouse gas emissions of wetland rice using life cycle assessment. *Journal of Cleaner Production*, 224, 72–87. https://doi.org/10.1016/j.jclepro.2019.03.215

Battaglia, M., Thomason, W., Fike, J. H., Evanylo, G. K., Cassel, M., Babur, E., Iqbal, Y., & Diatta, A. A. (2020). The broad impacts of corn stover and wheat straw removal for biofuel production on crop productivity, soil health and greenhouse gas emissions: A review. *GCB Bioenergy*, 13, 45–57. https://doi.org/10.1007/gcbbio.12774

Berhane, M., Xu, M., Liang, Z., Shi, J., Wei, G., & Tian, X. (2020). Effects of long-term straw return on soil organic carbon storage and sequestration rate in North China upland crops: A meta-analysis. *Global Change Biology*, 26(4), 2686–2701. https://doi.org/10.1111/gcb.15018

Blake, G. R., & Hartge, K. H. (1986). Bulk density. In A. Klute (Ed.), *Methods of soil analysis. Part I. Physical and mineralogical methods* (2nd ed., pp. 363–375). American Society of Agronomy.

Bolinder, M. A., Angers, D. A., Giroux, M., & Laverdière, M. R. (1999). Estimating C inputs retained as soil organic matter from corn (*Zea mays L.*). *Plant and Soil*, 215(1), 85–91. https://doi.org/10.1023/A:1004765024519

Bordonal, R. D. O., Carvalho, J. L. N., Lal, R., de Figueiredo, E. B., de Oliveira, B. G., & La Scala, N. (2018). Sustainability of sugarcane production in Brazil. A review. *Agronomy for Sustainable Development*, 38(2), https://doi.org/10.1007/s13593-018-0490-x

Bordonal, R. D. O., Menandro, L. M. S., Barbosa, L. C., Lal, R., Milori, D. M. B. P., Kolli, O. T., Franco, H. C. J., & Carvalho, J. L. N. (2018). Sugarcane yield and soil carbon response to straw removal in south-central Brazil. *Geoderma*, 328, 79–90. https://doi.org/10.1016/j.geoderma.2018.05.003

Carvalho, J. L. N., Hudiburg, T. W., Franco, H. C. J., & DeLucia, E. H. (2017). Contribution of above- and belowground bioenergy crop residues to soil carbon. *GCB Bioenergy*, 9(8), 1333–1343. https://doi.org/10.1111/gcbb.12411

Carvalho, J. L. N., Menandro, L. M. S., de Castro, S. G. Q., Cherubin, M. R., Bordonal, R. D. O., Barbosa, L. C., Gonzaga, L. C., Tenelli, S., Franco, H. C. J., Kollin, O. T., & Castioni, G. A. F. (2019). Multilocation straw removal effects on sugarcane yield in south-central Brazil. *Bioenergy Research*, 12(4), 813–829. https://doi.org/10.1007/s12155-019-10007-8

Carvalho, J. L. N., Nogueiro, R. C., Menandro, L. M. S., Bordonal, R. D. O., Borges, C. D., Cantarella, H., & Franco, H. C. J. (2017). Agronomic and environmental implications of sugarcane straw removal: A major review. *GCB Bioenergy*, 9(7), 1181–1195. https://doi.org/10.1111/gcbb.12410

Carvalho, J. L. N., Otto, R., Franco, H. C. J., & Trivelin, P. C. O. (2013). Input of sugarcane post-harvest residues into the soil. *Scientia Agricola*, 70(5), 336–344. https://doi.org/10.1590/S0103-90162013000500008

Castioni, G. A. F., Cherubin, M. R., Bordonal, R. D. O., Barbosa, L. C., Menandro, L. M. S., & Carvalho, J. L. N. (2019). Straw removal affects soil physical quality and sugarcane yield in Brazil. *Bioenergy Research*, 12(4), 789–800. https://doi.org/10.1007/s12155-019-10000-1

Cerri, C. C., Galdos, M. V., Maia, S. M. F., Bernoux, M., Feigl, B. J., Powelson, D., & Cerri, C. E. P. (2011). Effect of sugarcane harvesting systems on soil carbon stocks in Brazil: An examination of existing data. *European Journal of Soil Science*, 62(1), 23–28. https://doi.org/10.1111/j.1356-2389.2010.01315.x

Cherubin, M. R., Lisboa, I. P., Silva, A. G. B., Varanda, L. L., Bordonal, R. O., Carvalho, J. L. N., Otto, R., Pavinato, P. S., Soltangheshi, A., & Cerri, C. E. P. (2019). Sugarcane straw removal: Implications to soil fertility and fertilizer demand in Brazil. *BioEnergy Research*, 12(4), 888–900. https://doi.org/10.1007/s12155-019-10021-w

Conab. (2020). Acompanhamento da safra brasileira de cana-de-açúcar. Companhia Nacional De Abastecimento, Segundo Levantamento - Safra 2020/21, p. 115.

Dieckow, J., Bayer, C., Conceição, P. C., Zanatta, J. A., Martin-Neto, L., Milori, D. B. M., Salton, J. C., Macedo, M. M., Miichiczuk, J., & Hernani, L. C. (2009). Land use, tillage, texture and organic matter stock and composition in tropical and subtropical Brazilian soils. *European Journal of Soil Science*, 60(2), 240–249. https://doi.org/10.1111/j.1365-2389.2008.01101.x

Dignac, M.-F., Derrien, D., Barré, P., Lashermes, G., Maron, P.-A., Nunan, N., Roumet, C., Chevallier, T., Freschet, G. T., Garnier, P., Guenet, B., Hedde, M., Klumpp, K., Lashermes, G., Maron, P.-A., Nunan, N., Roumet, C., & Basile-Doelsch, I. (2017). Increasing soil carbon storage: mechanisms, effects of agricultural practices and proxies. A review. *Agronomy for Sustainable Development*, 37(2), 14. https://doi.org/10.1007/s13593-017-0421-2

Ellert, B. H., & Bettany, J. R. (1995). Calculation of organic matter and nutrients stored in soils under contrasting management regimes. *Canadian Journal of Soil Science*, 75(4), 529–538. https://doi.org/10.4141/cjss95-075

FAO. (2019). *Recarbonization of global soils*. Retrieved from http://doi.wiley.com/10.2136/ssabooksr5.3.e34

Goldemberg, J., & Guardabassi, P. (2010). The potential for first-generation ethanol production from sugarcane. *Biofuels, Bioproducts and Biorefining*, 4(1), 17–24. https://doi.org/10.1002/bbb.186

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DATA AVAILABILITY STATEMENT

The data is available in LNBR database.

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IPCC. (2019). Climate change and land - IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.

Johnson, J. M. F., Novak, J. M., Varvel, G. E., Stott, D. E., Osborne, S. L., Karlen, D. L., Lamb, J. A., Baker, J., & Adler, P. R. (2014). Crop residue mass needed to maintain soil organic carbon levels: Can it be determined? BioEnergy Research, 7(2), 481–490. https://doi.org/10.1007/s12155-013-9402-8

Kopittke, P. M., Dalal, R. C., Hoeschen, C., Li, C., Menzies, N. W., & Mueller, C. W. (2020). Soil organic matter is stabilized by organo-mineral associations through two key processes: The role of the carbon to nitrogen ratio. Geoderma, 357, 113974. https://doi.org/10.1016/j.geoderma.2019.113974

Kravchenko, A. N., Guber, A. K., Razavi, B. S., Koestel, J., Quigley, J. M. F., Novak, J. M., Varvel, G. E., Stott, D. E., Osborne, N., La Scala, N., Bolonhezi, D., & Pereira, G. T. (2006). Soil carbon sequestration impacts on global climate. Australian Journal of Soil Research, 45(1), 13–23. https://doi.org/10.1071/SR06080

Sanderman, J., Hengl, T., & Fiske, G. J. (2017). Soil carbon debt of 12,000 years of human land use. Proceedings of the National Academy of Sciences of the United States of America, 114(36), 9575–9580. https://doi.org/10.1073/pnas.1706103114

Segnini, A., Carvalho, J. L. N., Bolonhezi, D., Milori, D. M. B. P., Silva, W. T. L. D., Simões, M. L., Cantarella, H., Maria, I. C. D., & Martin-Neto, L. (2013). Carbon stock and humification index of organic matter affected by sugarcane straw and soil management. Scientia Agricola, 70(5), 321–326. https://doi.org/10.1590/S0103-90162013000500006

Silva-Olaya, A. M., Cerri, C. E. P., La Scala, N., Dias, C. T. S., & Cerri, C. C. (2013). Carbon dioxide emissions under different soil tillage systems in mechanically harvested sugarcane. Environmental Research Letters, 8(1), https://doi.org/10.1088/1748-9326/8/1/015014

Soil Survey Staff. (2019). A global agenda for collective action on soil carbon. Nature Sustainability, 2(2), 1436–1446. https://doi.org/10.1038/s41893-019-11057-4

Sousa Junior, J. G. D. A., Cherubin, M. R., Oliveira, B. G., Cerri, C. E. P., Cerri, C. C., & Feigl, B. J. (2018). Three-year soil carbon and nitrogen responses to sugarcane straw management. Bioenergy Research, 11(2), 249–261. https://doi.org/10.1007/s12155-017-9892-x

Spohn, M. (2020). Phosphorus and carbon in soil particle size fractions: A synthesis. Biogeochemistry, 147(3), 225–242. https://doi.org/10.1007/s10533-019-06633-x

Tenelli, S., de Oliveira Bordonal, R., Barbosa, L. C., & Carvalho, J. L. N. (2019). Can reduced tillage sustain sugarcane yield and soil carbon if straw is removed? Bioenergy Research, 12(4), 764–777. https://doi.org/10.1007/s12155-019-09996-3

Thorntwaite, C. W. (1948). An approach toward a rational classification of climate. Geographical Review, 38(1), 55–94. https://doi.org/10.2307/210739

van Raij, B., Andrade, J. C., Cantarella, H., & Quaggio, J. (2001). Decomposition of sugarcane straw: Basis of management decisions for bioenergy production. Biomass and Bioenergy, 122, 133–144. https://doi.org/10.1016/j.biombioe.2019.01.027

Xu, H., Sieverding, H., Kwon, H., Clay, D., Stewart, C., Johnson, J. M. F., Qin, Z., Karlen, D. L., & Wang, M. (2019). A global meta-analysis of soil carbon response to corn stover removal. GCB Bioenergy, 11(10), 1215–1233. https://doi.org/10.1111/gcbb.12631

Yang, W., Feng, G., Tewolde, H., & Li, P. F. (2019). CO2 emission and fossil and organic matter affected by sugarcane straw and soil management. Geoderma, 357, 113974. https://doi.org/10.1016/j.geoderma.2019.113974

Zhao, X., Liu, B.-Y., Liu, S.-L., Qi, J.-Y., Wang, X., Pu, C., Li, S.-S., Zhang, X.-Z., Yang, X.-G., Lal, R., Chen, F. U., & Zhang, S. (2019). A language and environment for statistical computing. R Foundation for Statistical Computing. Retrieved from https://www.r-project.org/
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