Soil & Tillage Research 237 (2024) 105976

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Quantity, quality and physical protection of soil carbon associated with sugarcane straw removal in southern Brazil

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ARTICLE INFO

Keywords:
Carbon stabilization
Mineral-associated organic matter
Particulate organic matter
Soil aggregation
Crop residues
Soil health

ABSTRACT

Sugarcane straw is identified as a potential energy feedstock to increase bioenergy production, but advances are required in understanding the straw removal impacts on soil organic carbon (SOC) stability and storage. The main objective of this study was to evaluate the quantity, quality and physical protection of SOC under areas with different straw removal rates over a six-year period. A field experiment was conducted in randomized blocks with four replications, including the following straw removal treatments: total removal (TR), high removal (HR), low removal (LR), and no removal (NR), corresponding to the quantities of 0, 5, 10 and 15 Mg ha^{-1} of dry straw maintained on soil surface, respectively. Effects of straw removal on SOC stocks and its temporal dynamics, as well as the rates of carbon (C) incorporated into the soil were evaluated to a 0.3-m depth. The effects on particulate organic matter (POM) and mineral-associated organic matter (MAOM) fractions were evaluated through physical fractionation of SOM. Finally, it was evaluated the distribution of aggregates, the C content of aggregates and the C preservation capacity (CPC) in fractions of aggregates. Our findings revealed that TR and HR decreased SOC stocks at 0.0–0.1 m and 0.0–0.3 m depths. The data indicated that about 24% of the C added via straw were retained in soil, and NR showed a SOC accumulation rate of 1.42 Mg ha^{-1} $year^{-1}$ relative to baseline. Low straw removal increased POM (46.2%) and MAOM (12.4%) in surface layer as compared to TR. The straw maintenance in the field increased the proportion of soil macroaggregates, resulting in higher amounts of C preserved in this fraction. Our findings suggest that maintaining 10 Mg ha^{-1} of straw was enough to favor physical protection and sustain storage of SOC over time. Therefore, the surplus of straw could be removed to produce bioenergy, although this management may hinder soil C sequestration and its benefits for sugarcane production and climate change mitigation.

1. Introduction

Increasing concentrations of carbon dioxide (CO_2) in the atmosphere cause environmental impacts that require investments for decarbonization strategies (Panos et al., 2023). Among these include the use of biorenewables to reduce greenhouse gases (GHG) emissions, and the development of agricultural management options to increase soil organic carbon (SOC) storage in agricultural areas (Hernandes et al.,

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https://doi.org/10.1016/j.still.2023.105976
Received 18 April 2022; Received in revised form 25 October 2023; Accepted 6 December 2023
Available online 15 December 2023
0167-1987/

2022). However, while inappropriate soil management practices can result in SOC losses, properly managed soils can promote SOC accumulation and improve soil health, as well as sustainable production in agroecosystems through reduced GHG emissions (Sanderman et al., 2017; Yu et al., 2020).

The global demand for biofuel feedstock has required sustainable changes in land management to increase the bioenergetic crops yield such as sugarcane crop (*Saccharum* spp.) (Bordonal et al., 2018a). Brazil is the world's largest producer of sugarcane (FAO, 2020), with an estimated production of 33.9 million tons of sugar and 24.8 billion liters of ethanol production in a cultivated area of 8.2 million hectares (Conab, 2021). The recent expansion of sugarcane management system to mechanized harvesting with no straw burning (green cane) has been triggered by the great effort to banish the negative environmental and socioeconomic issues associated with the pre-harvesting burning in the past years (Carvalho et al., 2017; Perillo et al., 2022). The changes in the sugarcane harvesting system resulted in the accumulation of straw (10–20 Mg ha^{-1}) maintained on soil surface during crop cycles, which has positive effects for SOC accumulation (Cerri et al., 2011; Bordonal et al., 2018a; Tenelli et al., 2021). However, there is no consensus on the quantity of straw to be removed from the soil surface to maintain soil functions and the provision of multiple ecosystem services (Cherubin et al., 2021).

In addition to the environmental benefits, straw has great potential to increase bioenergy production and reduce GHG emissions (Carvalho et al., 2019). The high energy potential of sugarcane straw makes it a strategic renewable feedstock for bioenergy purposes. Its usage has been encouraged by the RenovaBio program to increase the share of biofuels in the Brazilian energy matrix (MME, 2017), aiming to comply with international commitments (e.g., Paris Agreement; Glasgow Climate Pact) to mitigate global climate change. On the other hand, implications related to total or partial removal of straw from the field have raised concerns regarding additional carbon (C) emissions and potential impact on the sustainability of sugarcane agrosystems (Bordonal et al., 2018a). Several studies indicate that high rates of straw removal reduce SOC stocks (Sousa Junior et al., 2018; Carvalho et al., 2017; Morais et al., 2020; Popin et al., 2020; Tenelli et al., 2021), and affect the quality and stabilization of soil organic matter (SOM) (Bordonal et al., 2018b).

SOC formation is not only dependent on the balance between input and output of crop residues (Barré et al., 2018; Chenu et al., 2019), but also on the mechanisms of SOM stabilization. These mechanisms are defined as biochemical recalcitrance (Lehmann and Kleber, 2015), spatial inaccessibility and organo-mineral interaction (Lützow et al., 2006). Understanding how these mechanisms occur becomes important to conceptualize SOM as particulate organic matter (POM) and mineral-associated organic matter (MAOM) (Cotrufo et al., 2015; Lavallee et al., 2020), thus providing a more detailed insight into the straw removal impacts on the formation and persistence of SOM. Beyond improving the mechanistic understanding of SOC storage in the soil matrix, assessing POM and MAOM responses to straw removal can provide insights into the functionality and stability of SOM in tropical soils, which have very different properties and turnover rates (Cotrufo et al., 2019). While POM is largely made up of relatively undecomposed fragments that are quickly mineralized after entering into the soil, MAOM consists of microscopic fragments that have been chemically transformed by soil biota, persisting in the soil for long periods (Lavallee et al., 2020).

Therefore, the contribution of sugarcane straw to SOC stabilization by the formation of POM or MAOM is not well understood. According to Cotrufo et al. (2013), SOC stabilization depends on the efficient use of microbial substrate, since more labile substrates tend to form MAOM while more recalcitrant substrates form POM. As sugarcane straw is a low-quality crop residue with high C/N ratio and high content of polyphenols and lignin (Menandro et al., 2017), the investigation of straw removal effects on SOM fractions is therefore essential to decipher the controlling mechanisms of SOM stabilization. In addition, soil aggregates with an abundance of pore network are known to have a great contribution to physical protection and storage of SOC (Kravchenko and Guber, 2017). Since straw retention preserves soil structure (Castioni et al., 2018), a comprehensive understanding about the mechanisms governing SOC stability related to physical protection against microbial degradation is fundamental to design sustainable straw removal for bioenergy production.

This study is based on the hypothesis that high rates of sugarcane straw removal reduce SOC stocks over time, and these changes are driven by a decreased formation and physical protection of POM. Thus, the objective of this study was to evaluate the impacts of sugarcane straw removal on quantity, quality, and stabilization of SOC in a clayey Rhodic Eutrudox over a six-year period, aiming to obtain consistent information on the stabilization of SOM in tropical environments under sugarcane straw removal scenarios.

2. Material and methods

2.1. Description of the study area

The field experiment was established in September 2013, in a commercial sugarcane area in Iracemápolis, a city in the state of São Paulo, Brazil (coordinates 22° 36′ south latitude, 47° 34′ west longitude, at 614 m above sea level). The experiment was carried out on soil classified as a clayey Rhodic Eutrudox, according to USDA Soil Taxonomy (Soil Survey staff, 2014), this is, "Latossolo Vermelho eutroférrico", according to Brazilian Soil Classification System (Santos et al., 2018). The climate is defined as ST-UMi, a humid subtropical climate with dry winter, average temperature of 20.8 °C (Rolim et al., 2016), and annual average precipitation of 1.294 mm (Thornthwaite, 1948).

2.2. Experiment design

The experiment was established in September 2013 from a commercial sugarcane area cultivated with IAC95–5000 crop variety. The experimental area is relatively homogeneous under a flat relief. At that moment, soil chemical and physical analyses were performed for soil characterization, following the methodologies described by Raij et al. (2001) and Teixeira et al. (2017) (Table 1).

The experimental area was arranged in a randomized block design with four treatments and four replications, totaling 16 experimental plots. Dimensions of each individual plot were 10-m long by 12-m wide,

Table 1
Chemical and physical characterization of the experimental area during the establishment of the study in 2013.

Attributes	Soil Depth		
	0.0–0.1 m	0.1–0.2 m	0.2–0.3 m
pH $CaCl_2$	5.5	5.2	4.9
SOC (g kg^{-1})	28	19	17
P (mg dm^{-3})	95	25	17
K ($mmol_c$ dm^{-3})	13	10	9
Ca ($mmol_c$ dm^{-3})	90	45	28
Mg ($mmol_c$ dm^{-3})	52	23	12
H+Al ($mmol_c$ dm^{-3})	26	35	39
Sum of Bases ($mmol_c$ dm^{-3})	155	78	49
CEC ($mmol_c$ dm^{-3})	181	112	88
Base Saturation (%)	76	64	56
Sand (g kg^{-1})	226	242	220
Silt (g kg^{-1})	189	161	155
Clay (g kg^{-1})	584	597	626
Bulk density (Mg m^{-3})	1.35	1.40	1.40
Porosity (m^3 m^{-3})	0.46	0.50	0.49

SOC: soil organic carbon; P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium; H: hydrogen; Al: aluminum; SB: sum of bases; CEC: cation exchange capacity.

comprising eight sugarcane rows at 1.5-m spacing. Following the harvest of plant cane, four treatments were established from the remaining straw (on dry basis) on the soil surface, representing the following straw removal rates: total removal: (TR–0 Mg ha^{-1}), high removal (HR–5 Mg ha^{-1}), low removal (LR–10 Mg ha^{-1}) and no removal (NR–15 Mg ha^{-1}) (Fig. 1). The experiment setting up occurred annually after each harvesting, as follows: (i) annual quantification of straw using a metallic frame (0.25 m^2) randomly thrown ten times in the field; (ii) determination of straw moisture in the field using the AL-104 Agrologic® sensor coupled with E-831 Electrode; (iii) straw weighing in bags; and (iv) straw management in each treatment performed manually using rakes and forks. During the experimental period soil tillage was not performed, and the phytosanitary management and fertilization followed the technical management recommendations of the sugarcane mill.

2.3. Soil sampling

Soil samples were collected prior to the experimental set up (baseline) and continued every two years upon straw removal (2015, 2017 and 2019). In the field, one trench per plot (0.3 × 0.3 × 0.3 m) was opened in the inter-row position (0.2 m apart from sugarcane row) to collect disturbed and undisturbed soil samples from each of four soil depths (0.0–0.05, 0.05–0.1, 0.1–0.2, and 0.2–0.3 m) for determination of soil C concentration, bulk density, and fractionation of soil aggregates. Although straw removal can impact deeper soil layers on a long-term perspective, the present analysis was restricted to 0.3 m depth because this zone is more prone to changes in quantity and quality of soil C induced by straw removal rates on a mid-term basis (6 years).

2.4. Determination of SOC concentration and stock calculations

Disturbed samples were air-dried, after 10-g was ground, sieved using a 0.150-mm mesh sieve, and then analyzed by dry combustion method with a LECO® CN 628 Carbon Analyzer (Nelson and Sommers, 1996). In order to calculate soil C stocks, undisturbed soil samples were collected using volumetric rings (diameter 0.05 m × height 0.05 m) for bulk density determination. Then, the samples were weighed before and after oven drying at 105 °C to determine dry-weight basis. The bulk density (Mg dm^{-3}) was calculated by dividing the soil dry mass by the cylinder volume (Teixeira et al., 2017).

Soil C stocks for the 0.0–0.1 and 0.0–0.3 m layers were calculated as the sum of the stocks for all soil depths (0.0–0.05, 0.05–0.1, 0.1–0.2 and 0.2–0.3 m) according to Eq. (1):

$$Soil \quad C \quad stock \quad \left(Mg \quad ha^{-1}\right) = C \quad content \times bulk \quad density \times soil \quad layer \tag{1}$$

where, soil C stocks (Mg ha^{-1}) were obtained by multiplying soil C content (%) by bulk density (Mg m^{-3}) and soil layer (m).

Because soil samples were collected from previously mentioned layers (0.0–0.05, 0.05–0.1, 0.1–0.2 and 0.2–0.3 m), the soil C stock was adjusted for changes in bulk density that occurred after soil management. In order to adjust soil C stocks to an equivalent soil mass, the bulk density of the baseline characterization (before straw removal treatments; Table 1) was used as a reference to adjust the depths of the treatments TR, HR, LR, and NR according to the methodology described in Lee et al. (2009).

2.5. Annual rates of SOC loss/accumulation, carbon retention rates and temporal dynamics of SOC stocks

Losses and accumulations of SOC (Mg ha^{-1} year^{-1}) were also computed for the 0.0–0.1 and 0.0–0.3 m layers according to Eq. (2), which represents changes in SOC stocks induced by the straw removal treatments (TR, HR, LR and NR) in relation to baseline SOC stock in 2013 (e.g., before trials establishment).

$$SOC_{loss/accumulation} = \frac{SOC \quad stock \quad _{final} - SOC \quad stock \quad _{initial}}{Years} \tag{2}$$

where, *SOC loss/accumulation* is the annual rate of C loss or accumulation (Mg ha^{-1} year^{-1}) for four removal rates of straw (TR, HR, LR and NR) compared to initial SOC stock (baseline); *SOC stock$_{final}$* is the C stock (Mg ha^{-1}) related to each straw removal treatment in the last year of soil sampling (2019); and *SOC stock$_{initial}$* is the referential C stock (Mg ha^{-1})

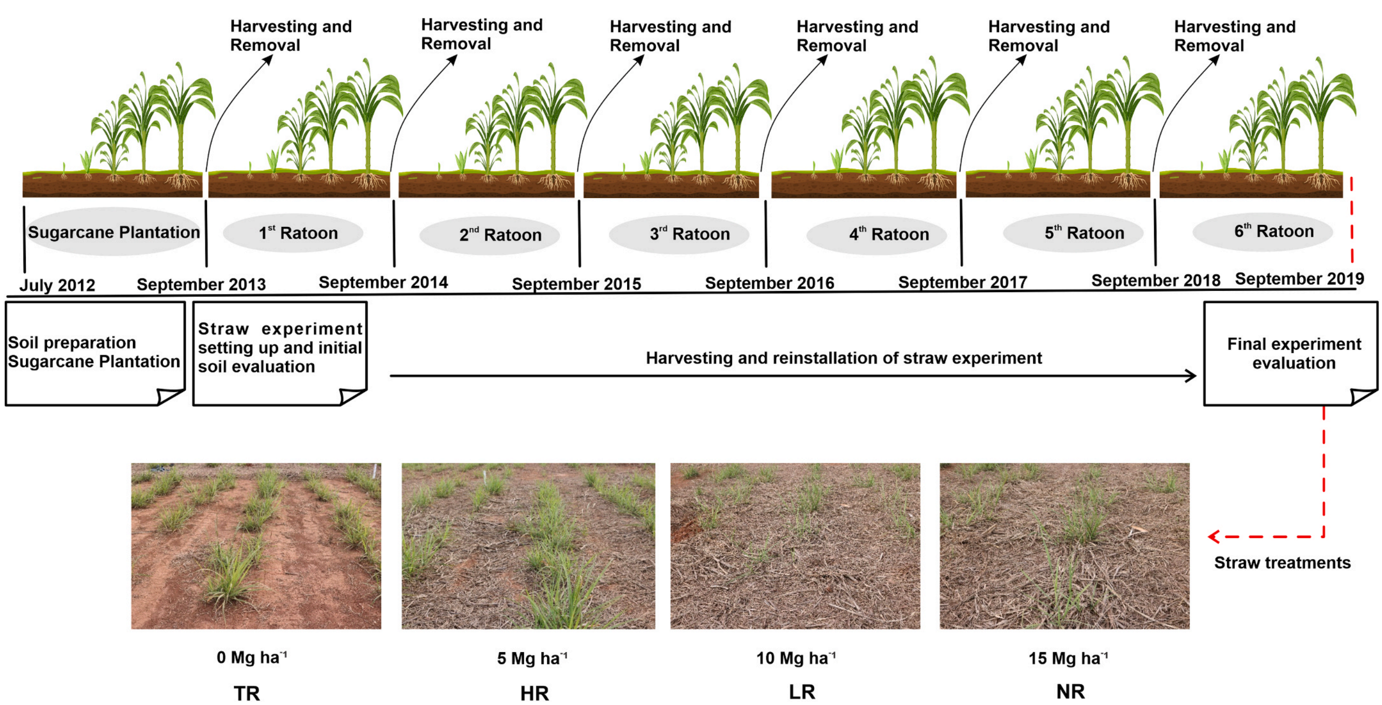

Fig. 1. Experimental period with different straw removal rates: TR – total removal, HR – high removal, LR – low removal, and NR – no removal. This study consisted of final experimental evaluation in 2019 (i.e., six years after establishing the trials).

before the establishment of trials (baseline); and *Years* represent the experimental timeframe of straw removal.

The ratio between cumulative straw inputs and SOC stocks was performed using a regression model with a relationship between SOC stocks over time (2015, 2017 and 2019) as a function of straw removal rates (Mg ha^{-1}) starting from baseline (2013). Regression analyses were also performed to explore the temporal dynamics of SOC stocks based on straw removal rates in relation to ΔSOC changes ($SOC_{final} - SOC_{initial}$) over the experiment timeframe. Data from baseline (2013) and intermediate years (2015 and 2017) for evaluation of SOC temporal dynamics and calculation of SOC accretion via cumulative straw input were extracted from Tenelli et al. (2021).

2.6. Aggregate size distribution, aggregate-associated carbon and its preservation capacity

For quantification of SOC concentration in aggregates of different sizes, undisturbed samples were gently passed through an 8-mm sieve by manually breaking up the soil along natural planes of weakness, and air dried for three days, following the approach recently applied by Franco et al. (2020). Soil aggregates were separated by using the wet-sieving method with a Yoder-type sieving (Elliott, 1986). Briefly, 50-g soil subsample was pre-wetted for 20 min on a 250 μm sieve at room temperature, and then subjected to wet sieving through a set of vertically oscillating sieves with thirty subsequent cycles per minute over a period of 10 min. The aggregate fractions remained on the 250 μm sieve (macroaggregates) and 53 μm sieve (microaggregates) and passed through the 53 μm sieve (silt and clay) were collected separately. Then, the aggregates fractions retained on the respective sieves were oven-dried at 40 °C for weighing and analyzing their SOC concentration by dry combustion method with a LECO® CN 628 Carbon Analyzer (Nelson and Sommers, 1996).

The SOC preservation capacity (CPC) of soil aggregates was calculated according to Eq. (3), aiming to have a better understanding of straw removal impacts on the variability of SOC concentrations, as recently applied by Chellappa et al. (2021).

$$CPC = \frac{WC_i \times WA_i}{100} \tag{3}$$

where, WC_i is the SOC concentration of the given aggregate particle size level (>250 μm or ≤ 250 μm) and WA_i is the content of aggregates (g) of a given particle size level (>250 μm or ≤ 250 μm).

2.7. Physical fractionation of soil organic matter

Soil organic matter was physically fractionated into particulate organic matter (POM) and mineral-associated organic matter (MAOM) for all soil depths: 0.0–0.05, 0.05–0.1, 0.1–0.2 and 0.2–0.3 m, following the particle-size method proposed by Cambardella and Elliott (1992). Briefly, 15 mL of sodium hexametaphosphate (5 g L^{-1}) solution was added to 5 g of soil (< 2 mm) and dispersed in a horizontal shaker for 16 h (140 rpm). Afterward, the dispersed solution was passed through a 53 μm mesh by gently adding a stream of distilled water. The coarse fraction (> 53 μm – POM) retained in the sieve and the flushed material (< 53 μm – MAOM) was stored in a recipient, oven-dried (40 °C), and ground (< 0.15 mm) for SOC determination by dry combustion on elemental analyzer – LECO® CN-628 (Nelson and Sommers, 1996). This process was performed in three replicates of each soil depth as a strategy to reduce the large number of samples to be analyzed.

2.8. Data analysis

The normality of errors was verified according to Shapiro-Wilk test at 5% significance and homogeneity of the variances by Bartlett's test ($p < 0.05$). After verification and acceptance of the assumptions, the data were subjected to analysis of variance (ANOVA) to evaluate the effects of straw removal rates on quantity, quality, and physical protection of SOC. When significant (test F $p < 0.05$), the means of the treatments were compared by Tukey's test ($p < 0.05$). Regression analyses were performed to investigate the relationship between SOC changes and cumulative straw inputs for consecutive years, as well as to explore the temporal dynamics of SOC over the experiment timeframe. All statistical analyses were performed using R software (R Core Team, 2020).

3. Results

3.1. Quantity and temporal dynamics of SOC stocks and conversion rate of straw-C input into SOC

After six years of straw management, SOC concentration ranged from 14.3 to 25.4 g kg^{-1} along the soil profile, and the highest values were found in the topsoil (0.0–0.05 m) for LR. Except for the 0.2–0.3 m depth, significant effects of straw removal rates on SOC content were observed (Fig. 2a). High rates of straw removal (HR and TR) caused SOC depletion at 0.0–0.05, 0.05–0.1 and 0.1–0.2 m depths, as compared to LR and NR treatments. In general, the SOC concentration in TR was 17.4% lower in relation to LR treatment for 0.0–0.05 m depth, while for 0.05–0.1 m and 0.1–0.2 m depths the losses caused by TR were 13.1% and 8.7% ($p < 0.05$) in relation to NR, respectively. LR and NR treatments showed similar results for SOC concentration. Straw removal had no significant effect on soil bulk density at any depths (Fig. 2b).

Results indicate that the SOC stock in NR and LR were higher than those for HR and TR in both 0.0–0.1 and 0.0–0.3 m layers (Fig. 3a, b). For the 0.0–0.1 m layer, NR and LR treatments presented higher SOC stock, around 12.4% and 12% in comparison with TR. Straw removal significantly affected SOC stock at 0.0–0.3 m layer, leading to depletions of SOC stock as the straw was removed. Lower SOC stocks were evident in TR and HR as compared to LR and NR treatments. Over the six years, LR and NR increased SOC stocks by 6.7 and 7.9 Mg ha^{-1} when compared to TR, respectively (Fig. 3b).

The LR and NR treatments resulted in rate of SOC accumulation of around 0.40 Mg ha^{-1} year^{-1}, while TR and HR resulted in losses of 0.20 and 0.02 Mg ha^{-1} year^{-1}, respectively compared to the baseline for the 0.0–0.1 m layer (Fig. 3c). All treatments presented SOC accumulation at 0.0–0.3 m layer, with LR and NR showing the highest accumulation rates of 1.23 and 1.42 Mg ha^{-1} year^{-1}, respectively (Fig. 3d).

The cumulative straw returned to the field for six consecutive years increased SOC stocks at both soil layers (Fig. 4a, b). The linear regression analysis shows that the cumulative straw input significantly ($p < 0.05$) affected SOC changes over a 6-year period. The results suggest that about 51 and 106 kg C ha^{-1} were retained into the soil for each Mg of sugarcane straw returned in the field at the 0.0–0.1 and 0.0–0.3 m-layers, respectively.

Regardless of the assessed soil layer (0.0–0.1 and 0.0–0.3 m), the temporal dynamics of SOC stocks indicated that the NR and LR treatments increased SOC accumulation over the years, while TR and HR presented SOC losses (Fig. 4c, d). A significant linear correlation ($p < 0.05$) of SOC accumulation was observed for NR and LR over time, indicating a higher positive impact of straw on the soil.

3.2. Straw management effects on the quality of soil organic matter

Changes in POM concentration were observed at 0.0–0.05 and 0.05–0.1 m ($p < 0.05$) layers (Fig. 5). The POM concentration along the soil profile ranged from 0.6 to 3.0 g kg^{-1}, corresponding to between 4% and 12% of total SOC. On the other hand, MAOM ranged from 13.7 to 22.4 g kg^{-1}, which represents from 88% to 96% of total SOC. Significant differences ($p < 0.05$) in POM concentration (3.0 g kg^{-1}) were observed for LR treatment, which was 46.2% higher in comparison with other treatments at 0.0–0.05 m depth. Likewise, POM concentration

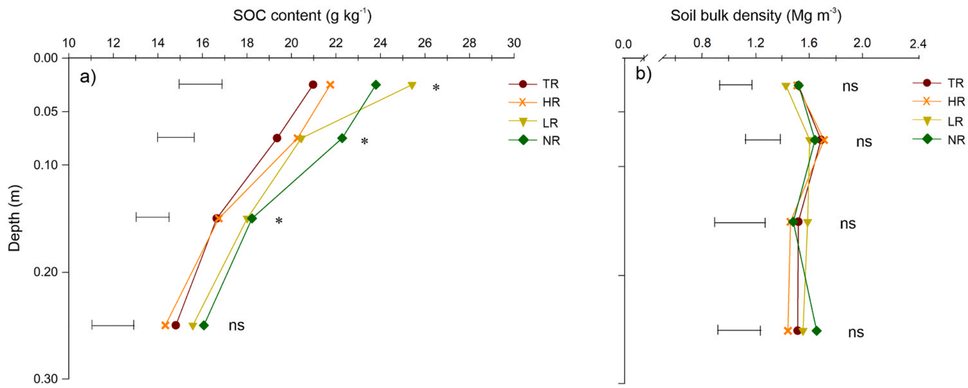

Fig. 2. SOC concentration (g kg^{-1}) (a) and soil bulk density (Mg m^{-3}) (b) to a 0.3 m depth (0.0–0.05, 0.05–0.1, 0.1–0.2 and 0.2–0.3 m) under different straw removal rates (TR – total removal; HR – high removal; LR – low removal; and NR – no removal). Bars refer to the least significant differences between data, and the asterisks indicate significant differences by Tukey's test ($p < 0.05$). *ns* = not significant.

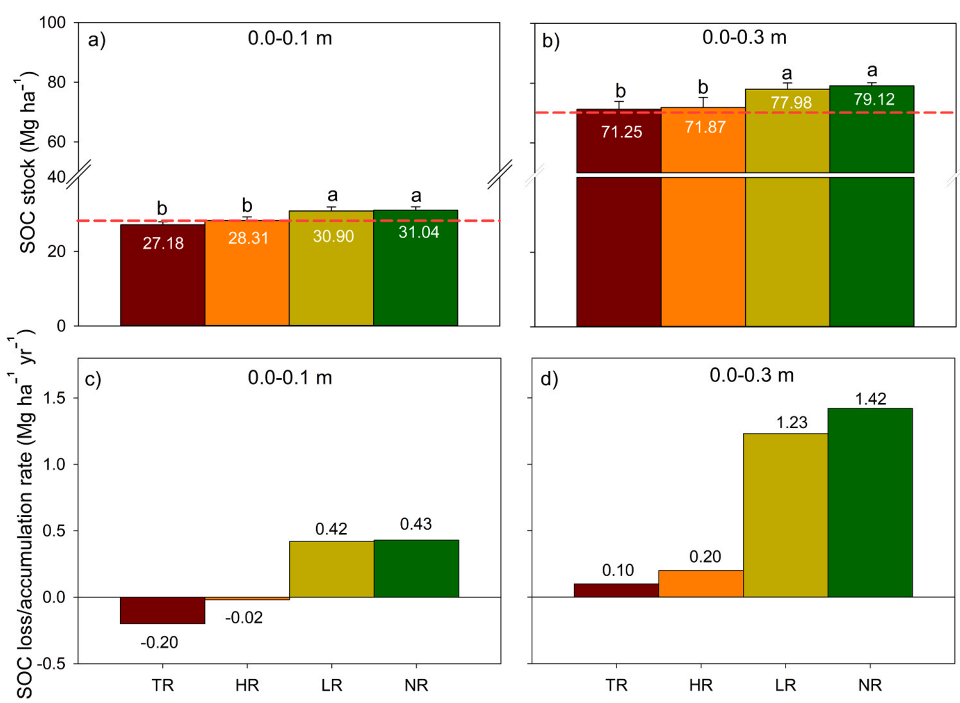

Fig. 3. SOC stocks (Mg ha^{-1}) (a-b) and annual rates of SOC accumulation and loss (Mg ha^{-1} $year^{-1}$) (c-d) at 0.0–0.1 and 0.0–0.3 m depths under straw removal rates (TR – total removal; HR – high removal; LR – low removal; and NR – no removal). The red dashed lines represent the baseline SOC stocks in 2013. Means followed by the same letter do not show significant differences among the treatments by Tukey's test ($p < 0.05$).

(1.5 g kg^{-1}) for NR was 23.5% higher in relation to other treatments at 0.05–0.1 m depth. Effects of neither of the treatments on POM and MAOM fractions were statistically significant for deeper layers (0.1–0.2 and 0.2–0.3 m).

Significant effects ($p < 0.05$) of straw removal on MAOM fraction were also observed at 0.0–0.05 and 0.05–0.1 m depths (Fig. 5). At both depths, NR and LR presented similar concentrations for MAOM fraction. The MAOM in LR (22.4 g kg^{-1}) was 12.6% higher than in TR (19.5 g kg^{-1}) in the surface layer. Similarly, the NR treatment (20.7 g kg^{-1}) showed a MAOM concentration of 12.4% higher as compared to TR (18.2 g kg^{-1}) for the 0.05–0.1 m depth. Overall, the POM was the most affected fraction by straw removal relative to MAOM. While straw management contributed to a 46.2% increase in POM fraction at 0.0–0.05 m layer, the modification of MAOM fraction was proportionally lower (12.6%) as compared to POM, suggesting that the six-year straw management has already begun to modify in a small proportion the most stable fraction of SOM.

3.3. *Straw management effects on soil aggregation and SOC distribution in aggregates*

The proportions related to the aggregate size distribution (%) were influenced to some extent by straw removal rates (Table 2). At all depths, higher percentage of macroaggregates (>250 μm) was observed as compared to microaggregates (53–250 μm) and silt + clay particles (≤ 53 μm). While straw removal had no significant effect on microaggregate class (53–250 μm), the macroaggregates were impacted by straw management at 0.0–0.05 m depth. The LR treatment presented an increase of 16% in the proportion of macroaggregates relative to TR. There was no difference among treatments for the silt + clay particles (≤ 53 μm) in the 0.0–0.05, 0.05–0.1 and 0.2–0.3 m depths. However, TR presented lower percentage ($p < 0.05$) for the silt + clay particles as compared to HR at 0.1–0.2 m depth (Table 2).

Distribution of the total SOC concentration was 87% in macroaggregates and 13% in microaggregates, which demonstrates the major

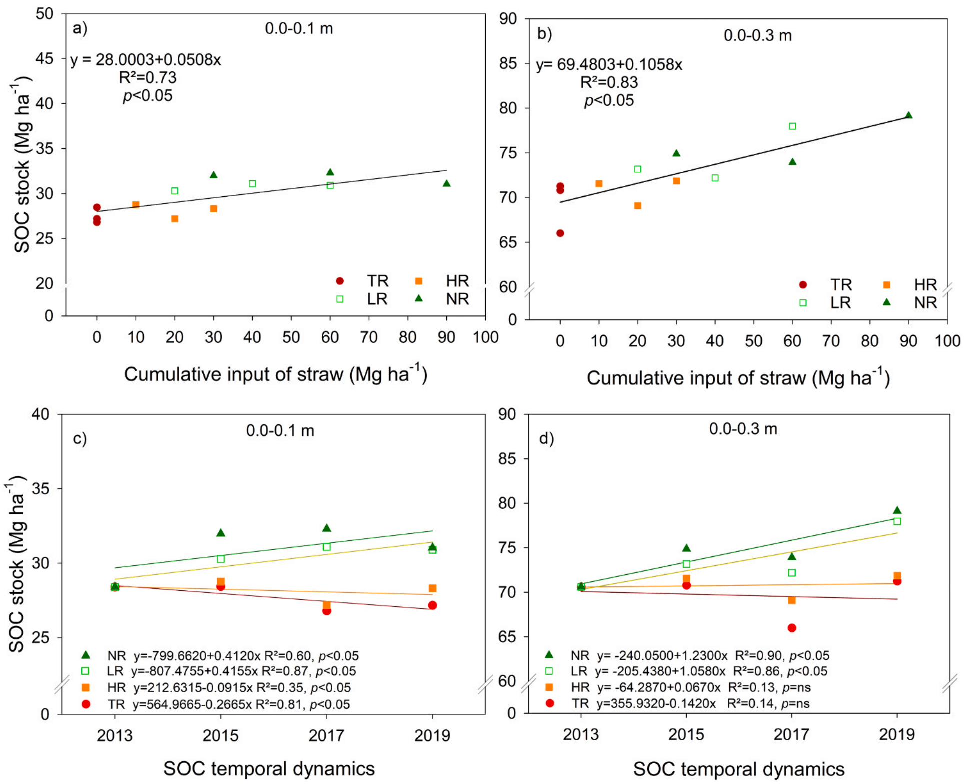

Fig. 4. (a-b) Relationship between the 6-year cumulative straw input and SOC stock at 0.0–0.1 and 0.0–0.3 m layers under different straw removal treatments (TR – total removal; HR – high removal; LR – low removal; and NR – no removal). Significant linear regression is represented by $p \leq 0.05$. Each of the three points of the evaluated treatments represents the evaluation intervals of 2, 4, and 6 years, corresponding to the years 2015, 2017 and 2019, respectively. The "*b*" value of the equation ($y = a + bx$) indicates kg of C in the soil per Mg of straw per hectare. (c-d) Temporal dynamics of SOC stocks in 6 years (c-d) at 0.0–0.1 and 0.0–0.3 m layers under different straw removal treatments (TR – total removal; HR – high removal; LR – low removal; and NR – no removal). *ns* = not significant.

contribution of macroaggregates in the storage and physical protection of SOC (Fig. 6). As for the SOC distribution in macroaggregates, the concentrations ranged from 12.5 to 22.6 g kg^{-1} with higher values in the topsoil (0.0–0.05 m). SOC concentration in macroaggregates was significantly affected ($p < 0.05$) by straw removal at 0.0–0.05 and 0.05–0.1 m depths. The LR treatment showed SOC concentration in macroaggregates 19.7% higher as compared to TR at the 0.0–0.05 m layer. In a comparison between NR and TR, the SOC concentration in macroaggregates was 12% (2.5 g kg^{-1}) higher at the 0.0–0.05 m layer. Additionally, the NR treatment presented higher (12.3%) SOC concentrations in macroaggregates as compared to TR at the 0.05–0.1 m layer. Unlike the results observed for macroaggregates, the SOC concentration in microaggregates was not significantly affected by straw management (Fig. 6).

3.4. Soil carbon preservation capacity (CPC)

The CPC analysis shows that a greater preservation of SOC occurs with increase in straw maintenance on the soil surface, especially in macroaggregates (Table 3). Straw removal influenced CPC at different depths and classes of soil aggregates. For the CPC in macroaggregates, the data ranged from 4.9 to 9.5 g kg^{-1} of C, with higher CPC at the surface and a reduction in CPC with increase in soil depth. Analysis of CPC in macroaggregates suggests that LR (9.5 g kg^{-1}) and NR (8.5 g kg^{-1}) increased CPC by 29% and 20% as compared to TR (6.8 g kg^{-1}) at the 0.0–0.05 m depth, respectively. No significant differences were observed at any other soil depth. No clear pattern could be detected for the CPC in microaggregates, whose values ranged from 0.1 to 0.2 g kg^{-1} (Table 3). However, no significant differences were observed at any soil depths, indicating that the CPC in microaggregates was less influenced by straw removal and presented higher stability.

4. Discussion

4.1. Soil carbon response to sugarcane straw removal

Experimental evidence from this study suggests that no or low straw removal rates (NR and LR) increased SOC stocks over six years (Fig. 3), while high rates of straw removal (HR and TR) proved to deplete SOC stocks in the topsoil (0.0–0.1 m). The inputs of aboveground residues in sugarcane fields are reportedly effective at enhancing SOC sequestration and improving soil health (Oliveira et al., 2017; Tenelli et al., 2021; Cherubin et al., 2021). A previous study using modeled data estimated that straw contributed to 70% of the total C input into sugarcane-cultivated soils (Carvalho et al., 2017), thus supporting our findings that indiscriminate straw removal may negatively impact SOC stocks and increase GHG emissions.

The potential contribution of straw to soil C was evidenced under the LR and NR treatments, showing a SOC accumulation rate of 1.23 and 1.42 Mg ha^{-1} year^{-1} at 0.0–0.3 m layer in relation to the baseline (Fig. 3d). These values are in line with previous estimates of an average SOC accumulation rate of 1.5 Mg ha^{-1} year^{-1} upon adoption of mechanized harvesting without burning in south-central of Brazil (Cerri et al., 2011). However, the magnitude of changes in SOC stocks may vary according to the study duration and site-specificity of soil type and climate conditions (Thorburn et al., 2012; Bordonal et al., 2018b; Amelung et al., 2020). For instance, effects on SOC sequestration can be even greater in clayey soils of tropical regions, in which the predominance of clay minerals like kaolinite and Fe and Al (hydr)oxides makes this type of soil less prone to SOC losses due to the high adsorption of organic molecules onto mineral surfaces (Dieckow et al., 2009; Kleber et al., 2021). Clay-textured soils are therefore more resilient to SOC losses over time, which may explain the higher SOC accumulation found

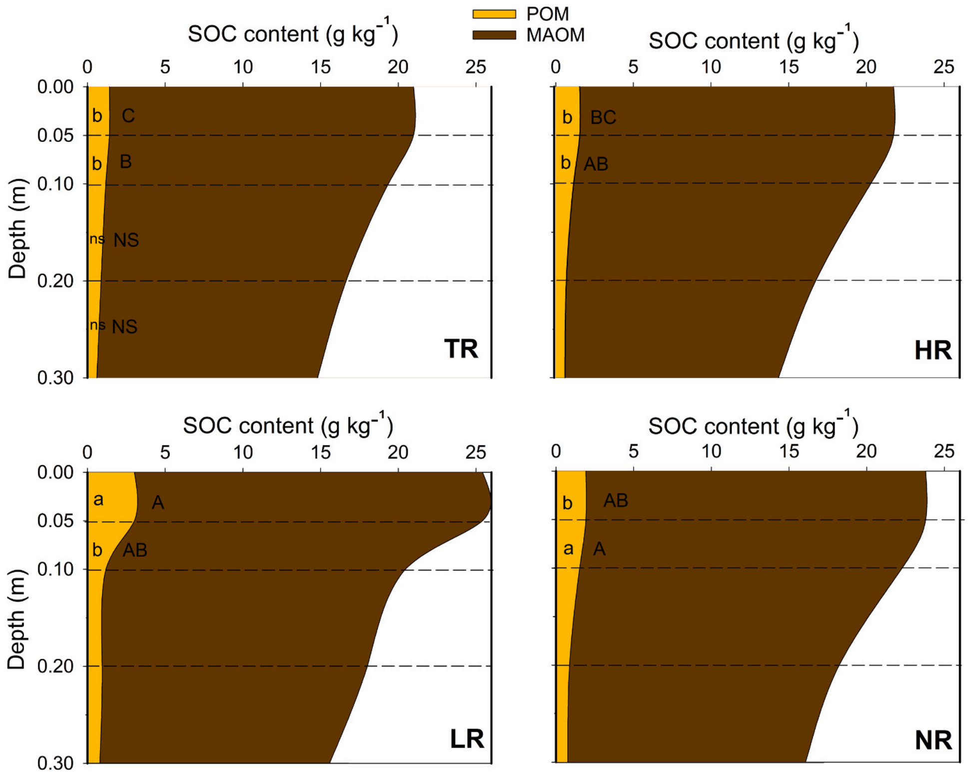

Fig. 5. SOC concentration in POM (particulate organic matter) and MAOM (mineral-associated organic matter) fractions under different straw removal rates (TR – total removal; HR – high removal; LR – low removal; and NR – no removal) for all assessed depths (0.0–0.05, 0.05–0.1, 0.1–0.2 and 0.2–0.3 m). Lowercase letters (in yellow) indicate differences among treatments in POM fraction, and uppercase letters (in brown) in MAOM fraction for each specific depth (dashed lines). Means followed by the same letter do not differ significantly among themselves by Tukey's test ($p < 0.05$). *ns* = not significant.

Table 2
Aggregate size distribution (%) in macroaggregates (>250 μm), microaggregates (53–250 μm), and silt + clay particles (≤ 53 μm) in different soil depths (0.0–0.05, 0.05–0.1, 0.1–0.2 and 0.2–0.3 m) based on straw removal rates (TR – total removal; HR – high removal; LR – low removal; and NR – no removal).

Aggregate Size (μm)	Soil depth (m)	Straw removal rates (Mg ha^{-1})			
		TR	HR	LR	NR
		Soil aggregate distribution (%)			
Macroaggregates (> 250 μm)	0.0–0.05	76.55 b	86.88 ab	90.72 a	86.61 ab
	0.05–0.1	88.64 a	89.16 a	86.91 a	91.05 a
	0.1–0.2	88.41 a	79.53 a	86.26 a	84.52 a
	0.2–0.3	78.97 a	82.95 a	85.56 a	87.79 a
Microaggregates (53–250 μm)	0.0–0.05	9.97 a	8.04 a	5.72 a	8.08 a
	0.05–0.1	5.81 a	7.92 a	9.41 a	6.52 a
	0.1–0.2	6.73 a	11.77 a	8.81 a	10.07 a
	0.2–0.3	12.76 a	11.41 a	10.08 a	7.27 a
Silt + Clay (≤ 53 μm)	0.0–0.05	13.47 a	7.58 a	5.32 a	6.97 a
	0.05–0.1	5.54 a	4.94 a	5.05 a	4.33 a
	0.1–0.2	4.85 b	10.05 a	6.88 ab	6.41 ab
	0.2–0.3	8.51 a	6.66 a	5.82 a	6.67 a

Means followed by the same letter do not differ significantly among themselves by Tukey's test ($p < 0.05$).

in our study.

Sugarcane straw contributed considerably to SOC accumulation through the cumulative quantity of straw returned to the soil over a six-year period (Fig. 4a, b). Considering that sugarcane straw presents a mean C concentration of 440 g kg^{-1} (Menandro et al., 2017), the data calculated by linear regression of cumulative returns showed that about 24% (106 kg C ha^{-1}) of straw-C inputs were retained in soil for each Mg of sugarcane straw returned in the field (Fig. 4b). This value is similar to those obtained in Brazilian sugarcane fields that showed a C incorporation via straw of 25% in clayey soils (Tenelli et al., 2021), which is higher than that of 13% found for Australian conditions (Robertson and Thorburn, 2007). The C retention rate found here is also higher than those observed in temperate climates by Bolinder et al. (1999) for corn stover (12%) and by Gale and Cambardella (2000) for oat straw (16%). However, our results represent the effects of straw on SOC during the sugarcane crop cycle and do not include the possible effects of tillage operations during the sugarcane replanting period. According to Segnini et al. (2013) and Tenelli et al. (2019), a significant portion of SOC accumulated by straw maintenance is lost due to tillage operations in sugarcane replanting period. Therefore, we advocate that further studies should be performed to evaluate the effects of straw removal on a long-term basis.

Despite the improper management of sugarcane straw can result in soil degradation in the long-term (Cherubin et al., 2021), its wise management can be a good strategy for enhancing SOC sequestration. The linear increase of SOC stocks over time in LR (10 Mg ha^{-1}) and NR (15 Mg ha^{-1}) treatments and the strong correlation between cumulative straw inputs and SOC stock indicate considerable opportunities for further SOC accrual in highly weathered tropical soils (Fig. 4), which are typically far from their C saturation capacity (Briedis et al., 2016). However, the potential for SOC stock increases in sugarcane fields should be realized through management strategies such as reduced soil

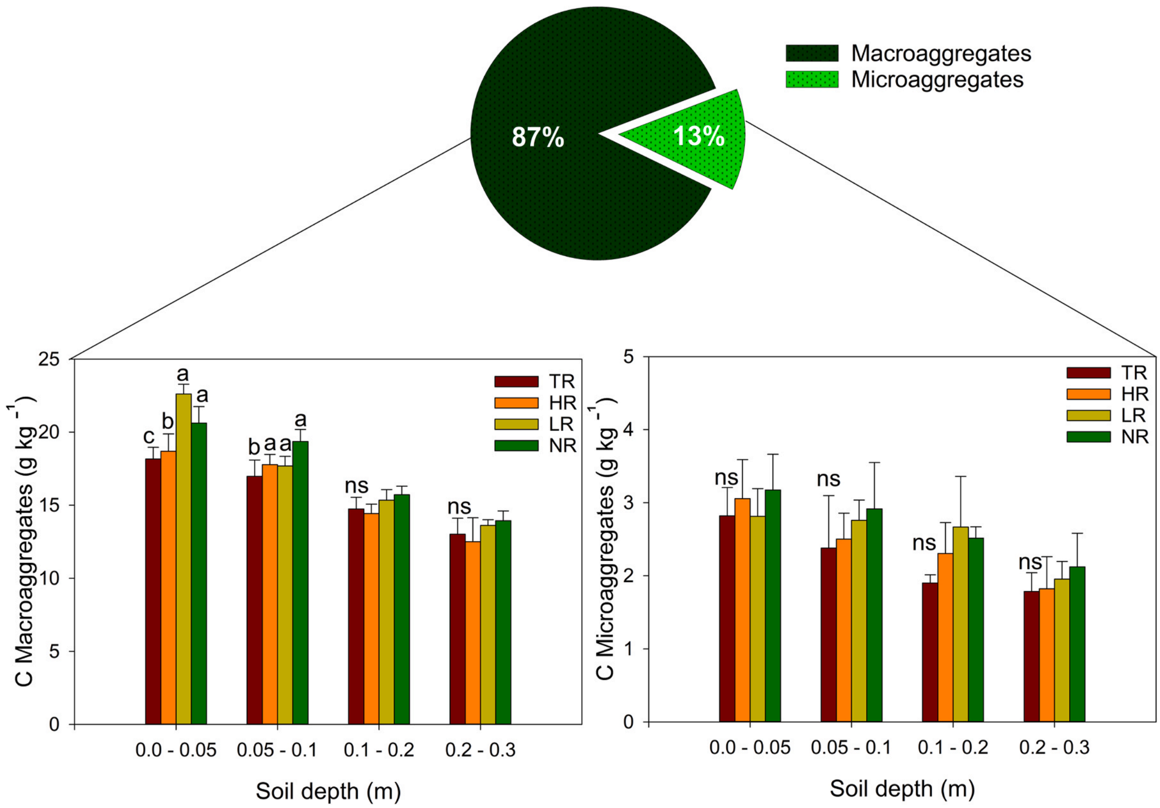

Fig. 6. Distribution (%) of the total SOC concentration (g kg^{-1}) in classes of macroaggregates (>250 µm) and microaggregates (≤ 250 µm) in different soil depths (0.0–0.05, 0.05–0.1, 0.1–0.2 and 0.2–0.3 m) based on straw removal rates (TR – total removal; HR – high removal; LR – low removal; and NR – no removal). Means followed by the same letter do not differ significantly among themselves by Tukey's test ($p < 0.05$). *ns* = not significant.

Table 3
Carbon preservation capacity (CPC) of soil aggregates (macroaggregates and microaggregates) influenced by different straw removal rates (TR – total removal; HR – high removal; LR – low removal; and NR – no removal) at different soil depths (0.0–0.05, 0.05–0.1, 0.1–0.2 and 0.2–0.3 m).

Aggregate Size (µm)	Soil depth (m)	Straw removal rates (Mg ha^{-1})			
		TR CPC (g kg^{-1})	HR	LR	NR
Macroaggregates (> 250 µm)					
	0.0–0.05	6.8c	7.5 b	9.5 a	8.5 a
	0.05–0.1	7.3 a	7.4 a	7.3 a	8.3 a
	0.1–0.2	6.3 a	5.3 a	6.2 a	6.3 a
	0.2–0.3	4.9 a	4.9 a	5.5 a	5.8 a
Microaggregates (< 250 µm)					
	0.0–0.05	0.21 a	0.23 a	0.18 a	0.23 a
	0.05–0.1	0.16 a	0.15 a	0.21 a	0.19 a
	0.1–0.2	0.10 a	0.16 a	0.22 a	0.19 a
	0.2–0.3	0.10 a	0.13 a	0.12 a	0.16 a

Means followed by the same letter do not differ significantly among themselves by Tukey's test ($p < 0.05$).

tillage and the use of cover crops with leguminous during sugarcane-replanting period combined with maintenance of crop residues to avoid soil health degradation.

Conclusions drawn from this study suggest that indiscriminate removal of sugarcane straw affects SOC preservation on a long-term basis, which corroborates previous studies reporting the short-term impacts of straw removal on SOC depletion in Brazilian soils (Morais et al., 2020; Tenelli et al., 2021). While complete straw removal should be avoided, an intermediate removal rate (keeping 10 Mg ha^{-1} of straw on soil surface) can be a management target to increase bioenergy production while sustaining the provision of multiple soil-related ecosystem services.

4.2. Lability of soil organic matter as affected by straw removal

Our findings reveal a more nuanced approach to understanding SOM lability, where POM was the most responsive fraction to straw removal, likely due to the relatively short duration (6 years) of this study, whereas MAOM was proportionally less responsive (Fig. 5). According to the Microbial Efficiency-Matrix Stabilization hypothesis (Cotrufo et al., 2013), more labile substrates with low C/N ratio are utilized more efficiently by microbes forming the MAOM, while more recalcitrant substrates with a high C/N ratio require high activation energy to be decomposed, tending to form POM. Sugarcane straw is characterized by a slow rate of decomposition, which is related to its high C/N ratio (100:1) and concentrations of lignin and polyphenols (Menandro et al., 2017). As observed for LR and NR treatments in the 0.0–0.05 and 0.05–0.1 m layers (Fig. 5), the data of this study suggest that low qualities of sugarcane straw tend to form more POM instead of MAOM fraction.

Although POM is considered a highly vulnerable fraction to environmental and management changes (Rocci et al., 2021), the increase in POM formation is commonly recognized as a strategy for enhancing and preserving SOC in soils with low N content (Kicklighter et al., 2019; Lugato et al., 2021), such as those in tropical environments. Typically, most soils have a POM contribution between 10% and 25% to their total SOC (Curtin et al., 2019), but in this study the contribution of POM represented about 8% of total SOC (Fig. 5). Given that this most labile fraction of SOM is not subject to saturation, accrual of POM provides a realistic opportunity to further increase SOC stocks in sugarcane fields where avoidance of complete straw removal is strongly supported by this study.

Even though MAOM was also affected by straw removal in the topsoil, the magnitude of these effects was much lower than those observed in POM (Fig. 5). While the LR treatment increased POM by 46.2%, the MAOM was affected by NR to a lesser extent (12.6%) as compared to TR. The allocation of a recalcitrant residue on soil surface has been reported to increase POM fraction while the formation of MAOM is less efficient (Sokol et al., 2019). The input of aboveground residues directly on soil surface is likely contributing to POM formation in surface layers, while the subsoil receives lower proportion of litter, favoring higher dissolved organic matter (DOM) and compounds of microbial origin that are important in the formation of MAOM (Zhang et al., 2021).

In essence, the SOM quality formed along the soil profile can vary vertically through direct sorption by MAOM translocation to the subsoil (Kaiser and Kalbitz, 2012). It is likely that straw removal might have affected the root system, thus decreasing C allocation in the subsoil and the formation of MAOM, as evidenced in TR (Fig. 5). Additionally, the C inputs via roots and exudates tend to form more microbial products (stable OM) as compared to aboveground residues (Cotrufo et al., 2015; Sokol et al., 2019). As sugarcane roots grow more vigorously in soil where straw is maintained on the surface (Melo et al., 2020), it is likely that more C is released into the rhizosphere (Jones et al., 2009), allowing for microbial abundance that stabilizes SOM more efficiently than aboveground residues (e.g., leachate from leaf litter). Consequently, preventing straw removal might have indirectly increased the microbial abundance in the rhizosphere that favored MAOM formation as compared to TR (Fig. 5). This is a promising hypothesis to be tested in future research.

The data showed that MAOM fraction stabilized in the soil ranged from 88% to 96% when considering the bulk SOC (Fig. 5), being this persistence mostly related to the strong interactions with clay minerals rather than the direct short-term effect of straw removal. The MAOM formation induced by straw management may have slowly increased over time, being this persistence already expected (Haddix et al., 2020; Lugato et al., 2021). Increases in MAOM are also explained by the soil characteristics such as clayey texture (Table 1) and mineralogy (Mitchell et al., 2020; Ramírez et al., 2021), which favors the MAOM formation through stabilization mechanisms such as organo-mineral interactions and occlusion within micropores or small aggregates (Lützow et al., 2008). Thus, our findings support the need of long-term experiments studying the responses of POM and MAOM rather than bulk SOM only, aiming to decipher the mechanisms by which straw management affects SOC stabilization in tropical soils.

4.3. Implications of straw management on aggregation, physical protection, and soil carbon preservation capacity

As important as understanding that soil management influences biomass-C input, the proper management for improving SOC stabilization is also critical to support soil health. The soil structure takes a long to be formed, but it can easily be dismantled with excessive soil disturbance (Or et al., 2021). Avoiding or reducing straw removal (NR, LR and HR) contributed to improve soil structure by increasing the proportion of macroaggregates (Table 2). This result is likely related to a dynamic balance between the formation of soil aggregates over the six-year period, as well as the reduction of soil disturbance by the straw mulching, which protects soil against erosion and reduces the aggregates breakdown (Sekaran et al., 2021). Similar results were found by Chellappa et al. (2021) using a conservationist management system without straw removal. In a recent study, Tenelli et al. (2019) found a SOC accumulation rate of 1.6 Mg ha^{-1} year^{-1} in clayey soils under a reduced soil tillage with all straw maintained, demonstrating the importance of preserving soil structure as a management target to sustain SOC sequestration in areas under straw removal.

The formation of soil aggregates is closely interconnected with the increase in SOC concentration induced by straw maintenance. The latter acts as a cementing agent that favors macroaggregation and aggregate stability (Table 2), thus promoting stabilization longevity of SOC through reduced access to microbial oxidation, as evidenced in LR and NR (Fig. 6). The results obtained here are in agreement with those obtained by Silva et al. (2021), who observed that no-removal of corn stover in a clayey Latosol also resulted in higher SOC content and macroaggregation. We conclude that while macroaggregation induced by straw maintenance controls SOC accrual, the latter emerges as a dynamic nucleus for the formation of microaggregates within macroaggregates because it provides energy for microbes to bind soil particles.

Even though the microaggregates play an important role in the SOC stabilization in temperate soils (Totsche et al., 2018), for tropical soils, macroaggregates have been highlighted as crucial to ensure the stabilization and subsequent accumulation of SOC (Tivet et al., 2013; Ferreira et al., 2018; Hok et al., 2021; Silva et al., 2021). In this study, straw favored the physical protection mechanism of SOC by occlusion (Fig. 6), which is a fundamental process for SOC persistence (Six et al., 2002; Guimarães et al., 2018). For example, the straw input in LR increased the SOC in macroaggregates by 19.7% in the topsoil layer (Fig. 6), demonstrating that in this system crop residues were transformed into SOM while decomposition occurs. It is well known that macroaggregates act as the initial storage stage for crop residues added to soil, while smaller fractions, such as silt + clay particles, tend to act as a final stabilization product (Liu et al., 2018). Recent studies revealed that the SOC flux occurs from macroaggregates to smaller fractions, including microaggregates and silt + clay particles (Liu et al., 2018; Atere et al., 2020). Therefore, low levels of straw removal can be a good strategy to increase macroaggregates that favor the physical protection of SOC, thus having a direct impact on SOC sequestration.

Since aggregates act in SOC preservation, high straw removal rates showed a reduced preservation capacity of soil carbon (CPC) due to lower aggregation (Table 3). Regardless of straw removal rates, higher CPC was observed for the macroaggregates fraction. The reason for this may be related to a higher preservation of the porous structure and a larger aggregation of particles (Sekaran et al., 2021; González-Rosado et al., 2023), thus indicating the potential of this fraction for enhancing SOC storage. Although macroaggregates showed higher CPC, the maintenance of sugarcane straw directly contributed to SOC by increasing its CPC, as shown in LR treatment where CPC increased by up to 29% (Table 3). This physical protection of SOC occurs as a result of physical barriers among decomposers and organic substances and/or environmental micro-conditions that restrict decomposers, which is driven by the characteristics of soil pore networks (Kravchenko and Guber, 2017). Deciphering the role of pore architecture driving SOC protection associated with straw management is a research priority.

Aggregate-associated SOC provides strength and stability and counters the impact of destructive forces (Hok et al., 2021), which increases the formation of microaggregates within macroaggregates (Denef et al., 2004). These results indicate that the CPC is intensified and SOC in macroaggregates tends to increase with decrease in straw removal (Fig. 6, Table 3). Therefore, the straw input over time is especially important for increasing SOC sequestration in the topsoil (Sekaran et al., 2021). Although the NR and LR treatments have influenced the increase in CPC of macroaggregates, the straw removal did not affect the CPC in microaggregates (Table 3), indicating that this fraction has low turnover and that SOC stabilization occurs over time. The preservation of SOC in microaggregates tends to have a longer stabilization when compared to macroaggregates due to slower turnover and greater SOC stability in microaggregates (Six et al., 2002). Our findings support the importance of maintaining part of sugarcane straw (LR and NR) in the field to increase soil macroaggregates that physically protect SOC against microbial degradation, thus favoring the long-term stabilization and accumulation of SOC in tropical environments.

5. Conclusions

Our findings revealed that total and high rates of straw removal reduced SOC stocks, and it should be avoided to ensure a sustainable straw management for bioenergy purposes. The adoption of low and no removal rates of sugarcane straw promoted better structuring and stability of aggregates demonstrated by greater distribution of soil macroaggregates, a condition that resulted in greater preservation capacity of SOC and increased SOC stocks over a 6-year period. Regarding the implications of straw removal to SOM quality, it was concluded that sugarcane straw greatly contributed to the formation of POM in relation to MAOM, specifically influenced by low removal rate.

Lastly, our findings suggest that an intermediate straw removal rate (the maintenance of 10 Mg ha^{-1} of straw) was sufficient to favor physical protection and sustain storage of SOC, while the removal rates above this limit tended to deplete SOC stocks.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This research was supported by the Sugarcane Renewable Electricity project – SUCRE/PNUD (grant number BRA/10/G31). The authors would like to express their appreciation to the São Paulo Research Foundation (FAPESP) for providing the research grants (Processes #2017/23978–7 and #2018/09845–7). We also thank to the National Council for Scientific and Technological Development– CNPq (Processes #427170/2018–4; #311787/2021–5). The first author also would like to give a special thanks to the Graduate Program in Soil Science of the College of Agricultural and Veterinarian Sciences, Sao Paulo State University (FCAV/UNESP), and the Coordination for the Improvement of Higher Education Personnel (CAPES) for granting the scholarship (processes 88887.492865/2020–00 and 88887.641540/2021–00), which was essential for the development of this research. Our most sincere gratitude also goes to the LNBR/CNPEM technical team for supporting our group during our laboratory analyses, and to Iracema Plant, from the São Martinho Group, for having made experimental areas available for our field experiments.

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