



Straw Removal Affects Soil Physical Quality and Sugarcane Yield in Brazil

Guilherme Adalberto Ferreira Castioni¹ · Maurício Roberto Cherubin² · Ricardo de Oliveira Bordonal¹ · Leandro Carneiro Barbosa¹ · Lauren Maine Santos Menandro¹ · João Luís Nunes Carvalho¹

Published online: 6 July 2019

© Springer Science+Business Media, LLC, part of Springer Nature 2019

Abstract

Industrial use of sugarcane straw for bioenergy production represents a promising opportunity for the Brazilian sugarcane sector. Nonetheless, intensified straw removal may aggravate the effects of mechanized harvesting and increase the risks of soil compaction, declining sugarcane yield. An experiment was designed, and four field studies were conducted to evaluate the cumulative effects of straw removal on soil physical attributes (bulk density, BD; soil resistance to penetration, SRP; macroporosity, MaP; microporosity, MiP, and mean weight diameter of soil aggregates, MWD) and their relationship with crop yield under clayey and sandy soils in the São Paulo state, Brazil. In each field study, four straw removal rates (no removal, NR; low removal, LR, removal of 5 Mg ha⁻¹; high removal, HR, removal of 10 Mg ha⁻¹; and total removal, TR, removal of 15 Mg ha⁻¹) were arranged in a randomized block design with four replicates. The 4-year intensive management of straw removal (HR and TR) resulted in an increased soil compaction (BD and SRP values) and reduced the MWD in both sandy and clayey soils. Our findings also showed that these effects are more significant in sandy soils, where soil carbon content was substantially reduced in HR and TR treatments. Sites with higher BD and SRP induced by straw removal were strongly associated with lower sugarcane yields, especially in sandy soils. Conversely, our findings indicate that LR was not detrimental to soil physical quality and sugarcane yield. Nevertheless, considering the multifunctionality of straw in sustaining multiple ecosystem services in different soil types, straw management should be defined taking into consideration site-specific conditions. We advocate that recommendations for straw removal should also be combined with other conservationist soil management practices in order to minimize soil compaction and its negative implications on sugarcane yield and other ecosystem services.

Keywords Soil compaction · Soil resilience · Oxisols · Crop residues · Stalk yield

Introduction

Brazil is the world's largest player in the production and utilization of renewable energies derived from sugarcane. Ethanol and bioelectricity produced from sugarcane have a positive energy balance and contribute to the mitigation of

environmental impacts caused by the greenhouse gas (GHG) emissions from fossil fuels [1]. The integral use of sugarcane represents an important market opportunity for the sugar-energy sector. As a consequence, in recent years, there has been an increasing interest of industries in collecting part of the straw left in the field for use in bioelectricity cogeneration and/or second-generation ethanol production [2]. However, in spite of the high potential for industrial use, the intensive removal of straw has been detrimental to several soil functions and associated ecosystem services [3], including decline of soil physical functionality in those areas [4].

Straw removal associated with highly mechanized production systems can intensify soil-related compaction problems, increasing soil bulk density [5] with consequent decrease in porous space and soil water fluxes. In addition, with intensive straw removal, the soil becomes exposed to the direct impacts of rain drops, causing disruption of soil aggregates [6],

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

¹ Brazilian Biorenewables National Laboratory (LNBR), Brazilian Center for Research in Energy and Materials (CNPem), 10000 Giuseppe Maximo Scolfaro Street, Polo II de Alta Tecnologia, Campinas, Sao Paulo 13083-100, Brazil

² “Luiz de Queiroz” College of Agriculture, University of São Paulo (ESALQ/USP), 11 Padua Dias Avenue, Piracicaba, Sao Paulo 13418-900, Brazil

superficial crust formation [7], and reduction of water infiltration, thus resulting in substantial increase of runoff and erosion risks [8].

Detrimental effects of indiscriminate straw removal on sugarcane yield are at odds with the expected bioenergy production to meet the increasing domestic and international demands. The maintenance of straw in the field can be beneficial to processes that sustain enhanced soil quality, especially carbon accumulation [9], one of the main elements acting in the formation and stabilization of soil aggregates, since it promotes a stable and complex porous network in the soil [10]. Straw maintenance also increases the wheel-soil contact area, dissipating wheel traffic loads [11]. It also attenuates temperature fluctuations and maintains soil moisture, favoring biological activity [12] and plant growth [13, 14].

Although the benefits of maintaining straw on soil surface are widely recognized [9], the impacts of its removal are not so easily predictable, since they vary according to soil type, climatic conditions, crop cycles, and management practices adopted in the area [14, 15]. Based on that, the amount of straw enough to preserve the soil physical quality varies according to the site-specific conditions [5]. However, most of the studies did not correlate alterations in soil physical quality with sugarcane yield. Thus, long-term studies focusing on contrasting conditions are fundamental for a better understanding of the straw removal relation with the soil physical quality and the associated impacts on crop yield.

This study was based on the hypothesis that the indiscriminate straw removal declines soil physical quality, causing detrimental effects to sugarcane crop yield. In order to test this hypothesis, an experiment was developed in four sites over a 4-year period for assessing the cumulative effects of straw removal on soil physical quality and their relationship with sugarcane yield in areas under contrasting edaphoclimatic conditions in the state of São Paulo, southeastern Brazil. In addition, this study also aimed to evaluate the effects of the harvesting season on soil physical quality and crop yield responses.

Material and Methods

Description of the Study Areas

The same field experiment was replicated in four sites, two in Iracemópolis (22° 34' S; 47° 31' W) and two in Quatá (22° 14' S; 50° 41' W), both cities located in the state of São Paulo (SP), southeastern Brazil. In all study areas, the treatments were established in 2013 upon harvesting of plant cane cycle. In each location, one experiment was established in April, at the beginning of the dry season, and another at the end of the harvesting period, at the onset of the rainy season in October. These locations

were characterized by contrasting soil textures. The clayey soils (i.e., Clayey_1 and Clayey_2), classified as Rhodic Eutradox, are located in Iracemópolis-SP, and the sandy loam soils (i.e., Sandy_1 and Sandy_2), classified as Arenic Kandiuult, are located in Quatá-SP (Table 1).

Experimental Design and Treatments

Each experimental field was arranged in a randomized block design with four treatments and four replicates, totaling 16 experimental plots. Each plot (10-m long by 12-m wide) comprised eight sugarcane rows spaced at 1.5 m. The treatments were established to evaluate the effects of equal rates of straw removal in contrasting soil conditions and harvesting seasons. In this study, we established an amount of 15 Mg ha⁻¹ of dry straw for the treatment named as no removal (NR), in which all straw is left in the field. Subsequently, three straw removal rates were established: (i) removal of 5 Mg ha⁻¹ (low removal, LR); (ii) removal of 10 Mg ha⁻¹ (high removal, HR); and (iii) removal of 15 Mg ha⁻¹ (total removal, TR). After the harvesting of each sugarcane cycle, the amount of straw on the soil surface was quantified using a metallic frame (0.25 m²) randomly thrown ten times in the field. Straw moisture measurement was performed directly in the field using the AL-104 Agrologic® sensor coupled with E-831 Electrode. Considering the 4 years of study, the Clayey_1, Clayey_2, Sandy_1, and Sandy_2 sites produced, on average, 12.4 Mg ha⁻¹ (ranging from 13.7 to 10.1), 11.4 Mg ha⁻¹ (ranging from 14.8 to 8.9), 9.6 Mg ha⁻¹ (ranging from 14.6 to 9.3), and 11.9 Mg ha⁻¹ (ranging from 14.7 to 9.9), respectively. The adjustment of the exact amount of straw within each treatment was performed manually using rakes and forks. In all sites, the plots received annual fertilization of 120 kg ha⁻¹ of nitrogen (ammonium nitrate) and potassium (potassium chloride). Applications of fungicides, insecticides, and herbicides were uniform in all treatments and conducted according to the management strategies established by the sugarcane mill.

Sampling and Soil Physical Measurements

In 2017, after harvesting the fourth sugarcane ratoon, the soil was sampled in all sites for the assessment of cumulative effects of straw removal on soil physical quality over a 4-year period. Undisturbed soil samples were collected using metal rings (0.05 m in diameter and 0.05 m in height). Additionally, soil monoliths were collected from two sites, Clayey_1 and Sandy_1, for the evaluation of soil aggregates stability. Trenches (1.40 × 0.90 × 0.30 m) were opened crosswise in relation to the crop row,

Table 1 Characterization of experimental fields during the establishment of the study in 2013

Site description	Clayey 1	Clayey 2	Sandy 1	Sandy 2
Location	Iracemápolis-SP	Iracemápolis-SP	Quatá-SP	Quatá-SP
Geographic coordinates	22° 34' S–47° 31' W	22° 36' S–47° 34' W	22° 12' S–50° 50' W	22° 19' S–50° 38' W
Altitude above sea level (m)	631	613	518	541
Mean annual rainfall (mm)	1420	1420	1391	1391
Mean annual temperature (°C)	20.4	20.4	23.7	23.7
Climate type*	Cwa, humid subtropical, dry winter	Cwa, humid subtropical, dry winter	Aw, tropical moist	Aw, tropical moist
Sugarcane variety	RB96-6928	IACSP-5000	RB96-6928	RB86-7515
Soil type (USDA-soil taxonomy) [†]	Rhodic Eutrudox	Rhodic Eutrudox	Arenic Kandiuult	Arenic Kandiuult
Chemical attributes (0–20 cm) ^a				
pH CaCl ₂	5.4	5.3	5.3	4.9
C content (g kg ⁻¹)	25.9	23	5.7	4.7
P (mg dm ⁻³)	87	60	9	9
K (mmol _c dm ⁻³)	20	11	1	1
Ca (mmol _c dm ⁻³)	54	67	37	18
Mg (mmol _c dm ⁻³)	22	37	4	6
H+Al (mmol _c dm ⁻³)	16	30	9	14
CEC (mmol _c dm ⁻³)	112	146	51	39
Base saturation (%)	85	70	81	61
Physical attributes				
Clay content (g kg ⁻¹)				
0–10 cm	556	584	92	68
10–20 cm	578	597	100	75
20–40 cm	597	626	142	90
40–60 cm	633	650	170	179
60–100 cm	628	618	178	190
Bulk density (Mg m ⁻³)				
0–10 cm	1.32	1.35	1.63	1.66
10–20 cm	1.33	1.40	1.72	1.73
20–40 cm	1.29	1.40	1.68	1.76
40–60 cm	1.39	1.40	1.62	1.63
60–100 cm	1.36	1.39	1.56	1.47

* According to Alvares et al. [16]

[†] Soil survey according to Soil Survey Staff [17]

^a Soil chemical analysis according to Raji et al. [18] and soil texture according to Teixeira et al. [19]

from the center to the middle of the inter-row position. Thereafter, samples were collected from the inter-row at four soil depths (i.e., 0–0.05, 0.05–0.10, 0.10–0.20, and 0.20–0.40 m).

In laboratory, samples of undisturbed soil were gradually saturated with water by capillarity action and weighed. After total saturation, the samples were carried over to the tension table to estimate microporosity (MiP, m⁻³ m⁻³) at the soil water potential (Ψ) of – 6 kPa [19]. Macroporosity (MaP, m⁻³ m⁻³) was determined by the difference between microporosity and total porosity. The

total porosity (TP, m⁻³ m⁻³) was estimated according to Teixeira et al. [19] using soil particle density. Bulk density (BD, Mg m⁻³) was calculated by dividing the soil dry mass obtained at 105 °C for 48 h by the volume of the cylinder, as described by Teixeira et al. [19].

Soil resistance to penetration (SRP, MPa) was obtained after porosity determination using the soil water content of the sample at – 6 kPa. An electronic penetrometer with a 4-mm tip and a constant penetration speed of 10 mm s⁻¹ was used. Measures were obtained from the center of undisturbed soil samples. Measures from the upper (0.01

m) and lower portions (0.01 m) were excluded from all samples, following the procedures as described in Inhoff et al. [20].

Soil monoliths were air-dried and later passed through sieves to obtain soil aggregates with diameters between 4.75 and 8 mm. The assessments followed the methodology as described by Kemper and Chepil [21], which uses a 50-g air-dried soil sample moistened by capillarity for 10 min. Subsequently, these samples were transferred to a set of sieves in vertical oscillation (Yoder-type sieving) in water for 15 min. The aggregates were separated in the following classes: C1 (9.52–4.76 mm), C2 (4.76–2.0 mm), C3 (2.0–1.0 mm), C4 (1.0–0.5 mm), C5 (0.5–0.25 mm), and C6 (< 0.25 mm). The content of each sieve was air-dried at 105 °C for 24 h and weighed. Soil aggregate stability for each sample was then expressed by the mean weight diameter (MWD, mm) using Eq. (1):

$$MWD = \sum_{i=1}^n \bar{x}_i \times w_i \quad (1)$$

where, \bar{x}_i is the mean diameter (mm) of size fraction and w_i is the weight of each size fraction of aggregates of total sample.

For the soil organic carbon (SOC) concentration analysis, composite soil samples were collected from the row and inter-row positions in the same layers, as described above. Soil samples were air-dried and sieved through a 2-mm sieve. After that, 10 g of each sample was ground and sieved through a 0.25-mm sieve for measurements of the total C concentration by the dry combustion method using a Carbon Analyzer—LECO® CN-628.

Sugarcane Stalk Yield

Sugarcane stalk yield was quantified over 4 years for the harvest of 2013–2014 (first ratoon), 2014–2015 (second ratoon), 2015–2016 (third ratoon), and 2016–2017 (fourth ratoon) in the four experimental fields. Each plot was mechanically harvested, and the stalk yield of the four central rows was computed using an instrumented truck equipped with a loading cell (used exclusively for the experiments).

Statistical Analysis

Statistical analysis of each site was performed according to a randomized block design with four repetitions. Data normality was confirmed by the Shapiro-Wilk's test at the 5% significance level. Analysis of variance (ANOVA) was performed to test the effects of straw removal on soil physical attributes and SOC content. The average yield of the four harvests was calculated for evaluation of the effects of straw removal

treatments. When statistically significant (F test $p < 0.05$), the means were compared according to Tukey's test ($p < 0.05$). A principal component analysis (PCA) was carried out to reveal multiple relations among soil physical attributes, SOC, and sugarcane yield under straw removal rates. All statistical analyses were performed using the R software [22].

Results

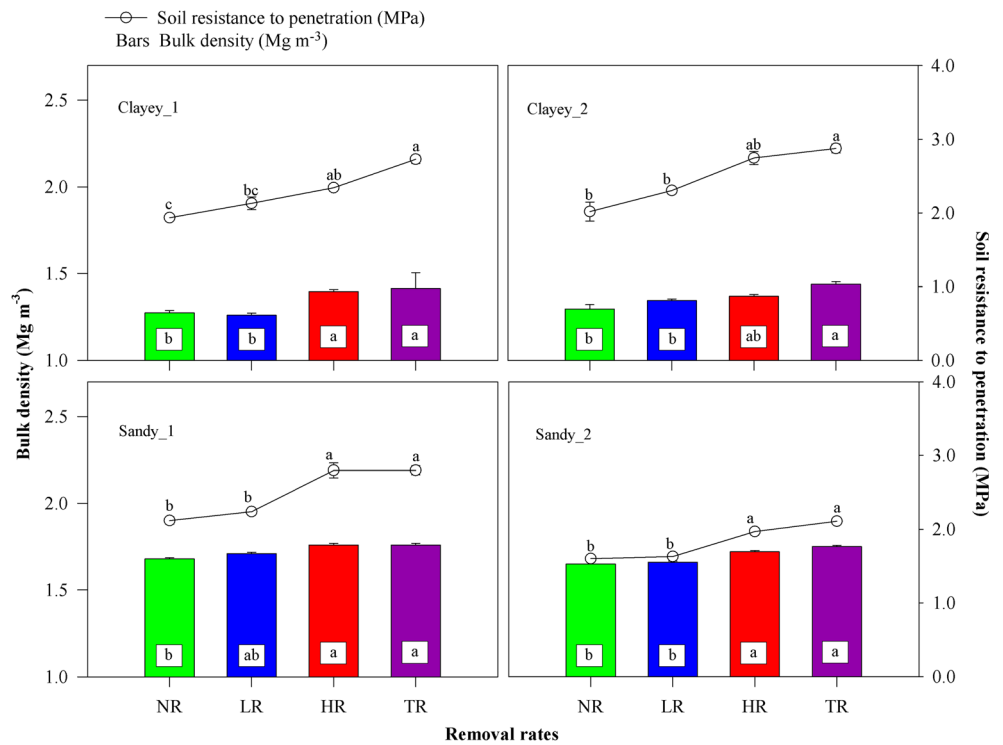
Soil Resistance to Penetration and Bulk Density

After 4 years, the straw removal promoted significant increases in SRP and BD in the 0–40 m soil layer of the four sites. In Clayey_1, the average SRP in the TR (2.73 MPa) treatment was 28% and 41% greater than in LR (2.13 MPa) and NR (1.93 MPa), respectively (Fig. 1). Similar pattern was observed in Clayey_2, with increases of 25% and 42% in TR (2.88 MPa) as compared with LR (2.30 MPa) and NR (2.02 MPa), respectively. In sandy soils, significant increases were also observed in SRP with the highest straw removal rates (i.e., HR and TR). In Sandy_1, SRP under TR and HR was 25% and 32% greater in comparison with LR (2.24 MPa) and NR (2.12 MPa), respectively, while in Sandy_2, the average SRP in TR (2.11 MPa) was 30% and 32% greater in relation to LR (1.63 MPa) and NR (1.60 MPa), respectively (Fig. 1). High values of BD were observed for the TR and HR treatments (0–40 m depth), reaching maximum values of 1.40 and of 1.76 Mg m⁻³ in clayey and sandy soils, respectively (Fig. 1).

Significant increases in SRP occurred under TR and HR, presenting SRP values above 2 MPa in the four evaluated sites. For instance, TR treatment in Clayey_1 showed SRP increases in the four soil layers (0.0–0.05, 0.05–0.10, 0.10–0.20, 0.20–0.40 m) in relation to LR and NR treatments, reaching values close to 3 MPa (Fig. 2). In the same site, SRP under HR had higher values than LR and NR in the 0.05–0.10 and 0.10–0.20 m layers. In Clayey_2, the HR presented greater SRP only in the surface layer (0.00–0.05 m) in comparison with NR. Similar response was observed under TR for the 0.05–0.10, 0.10–0.20, and 0.20–0.40 m layers in Clayey_2.

In sandy soils, the SRP under HR in Sandy_1 was higher compared with those under other treatments in the 0.00–0.05 m layer. Still in this site, the same pattern was observed for SRP under TR in comparison with NR in the 0.20–0.40 m layer. In Sandy_2, HR and TR promoted increments in the SRP values as compared with NR in the 0.05–0.10 and 0.10–0.20 m layers (Fig. 2). In Clayey_1, BD had an increase under HR and TR in the 0.05–0.10 m layers, while in the 0.0–0.05, 0.10–0.20, and 0.20–0.40 m layers only HR differed from NR and LR (Fig. 3). In Clayey_2, higher BD values were observed

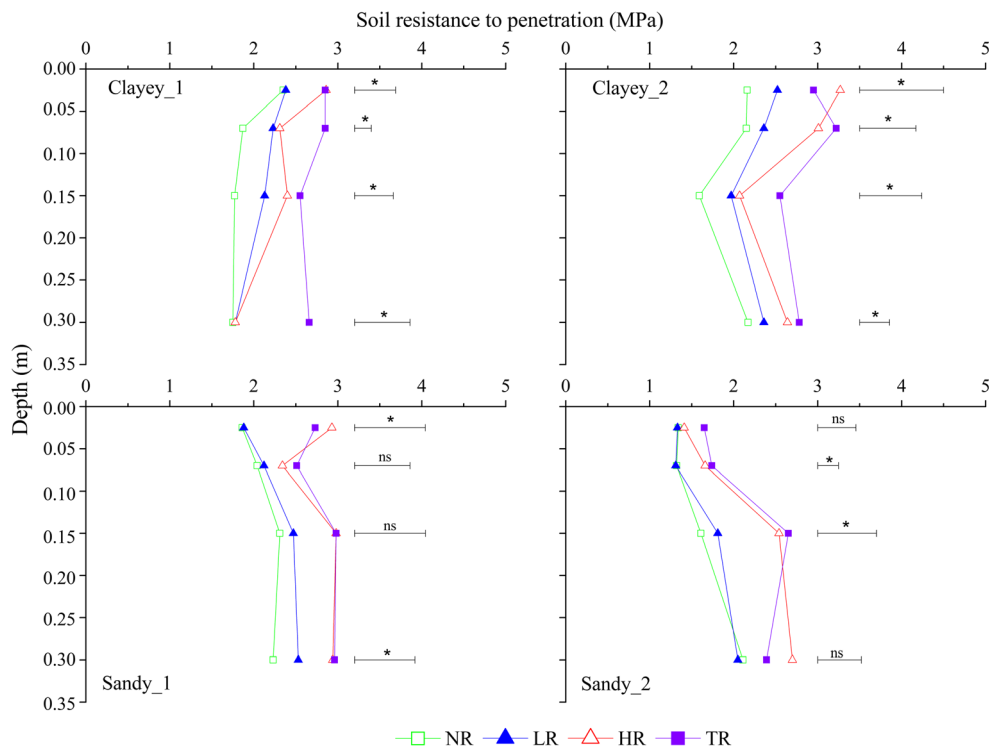
Fig. 1 Cumulative effects of sugarcane straw removal (NR, no removal; LR, low removal; HR, high removal; and TR, total removal) on soil physical quality indicators (soil density, BD, Mg m^{-3} and soil resistance to penetration, SRP, MPa) in the 0–0.40 m layer in clayey and sandy soils. Means followed by same letter within bars do not differ among themselves according to the Tukey’s test ($p < 0.05$)



in HR and TR in the upper soil layer (0.05–0.10 m) in relation to LR and NR. For the same site, higher BD values under TR were observed in the 0.0–0.05 and 0.20–0.40 m soil layers than in other treatments. In Sandy_1, HR and TR treatments increased BD values in

the 0.0–0.05 layer, and NR show low BD in the 0.10–0.20 and 0.20–0.40 m soil layers. In Sandy_2, significantly higher BD values were observed under TR treatment in comparison with LR and NR in the 0.05–0.10 and 0.20–0.40 m layers (Fig. 3).

Fig. 2 Cumulative effects of sugarcane straw removal (NR, no removal; LR, low removal; HR, high removal; and TR, total removal) on soil resistance to penetration (SRP, MPa) in the 0.0–0.05, 0.05–0.10, 0.10–0.20, and 0.20–0.40 m layers in four sites (Clayey 1 and 2 and Sandy 1 and 2). * indicates significant difference according to Tukey’s test ($p < 0.05$). ns, not significant



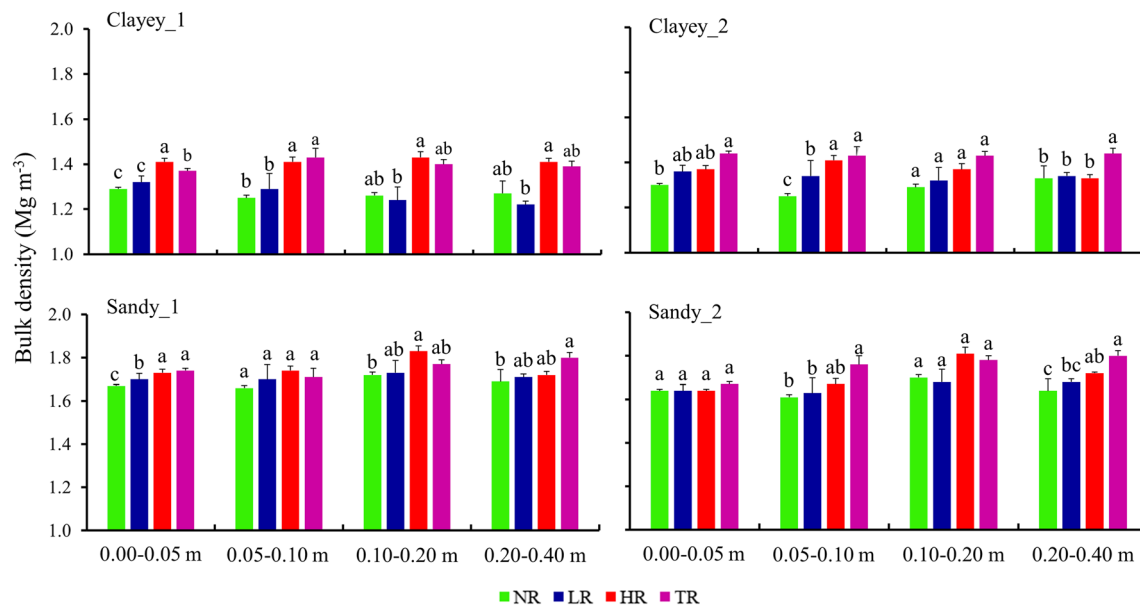


Fig. 3 Cumulative effects of sugarcane straw removal (NR, no removal; LR, low removal; HR, high removal; and TR, total removal) on soil bulk density (BD, Mg m^{-3}) in the 0.0–0.05, 0.05–0.10, 0.10–0.20, and 0.20–

0.40 m layers in four sites (Clayey 1 and 2 and Sandy 1 and 2). * indicates significant difference according to Tukey's test ($p < 0.05$). ns, not significant

Soil Porosity

Soil porosity was reduced under TR and HR treatments (Table 2). In Clayey_1, MaP was significantly higher under NR and LR than under HR in the 0.10–0.20 m layer. Similar effects were observed in Clayey_2, where lower MaP was observed in HR and TR as compared with LR in the 0.0–0.05 m soil layer, while in the 0.10–0.20 m HR and TR presented lower MaP relative to LR and NR. In the same site, TR also presented reduced levels of MiP in relation to NR in the 0.05–0.10 m layers. In Sandy_1, TR reduced MiP value in comparison with NR in the 0.0–0.05 and 0.10–0.20 m layers, while in Sandy_2, no alterations were observed in MiP as a result of straw removal management.

Mean Weight Diameter (MWD) of Soil Aggregates

Intensive straw removal (i.e., HR and TR) reduced MWD of soil aggregates in the Clayey_1, with a difference around 18% under TR as compared with NR in the 0.0–0.5 m layer (Fig. 4). Straw removal effects on MWD were not detected in deeper soil layers. In the Sandy_1, the aggregate stability decreased as straw was removed from the soil, indicating significant differences in MWD under NR treatments in relation to other treatments in upper layers (0.0–0.5 m). The LR and NR treatments presented greater MWD than TR in the 0.05–0.10 and 0.10–0.20 m layers.

Soil Organic Carbon (SOC) Content

Intensive straw removal rates (TR and HR) declined SOC contents. In sites under clayey soils, TR induced SOC

depletion in the surface layers (0.0–0.05 and 0.05–0.10 m) in comparison with NR. In Sandy_1, a significant change was found in the 0–0.05 m soil layer, and high SOC content was observed in NR, followed by LR, HR, and TR. The SOC content in this soil layer decreased 2.6-fold under TR (4.14 g kg^{-1}) in relation to NR (11.00 g kg^{-1}).

Sugarcane Stalk Yields

Average sugarcane stalk yields were not affected by straw removal management in Clayey_1 and Clayey_2 (Fig. 6). In contrast, substantial reductions in stalk yield were caused by straw removal in sandy loam soils. In Sandy_1, higher stalk yield was observed in NR, followed by LR, HR, and TR. Yield differences between the most contrasting treatments (NR and TR) were of 14 Mg ha^{-1} for sugarcane stalks. Similar response occurred on Sandy_2 with higher yields under NR and LR treatments than under HR and TR.

Relation Between Soil Attributes and Sugarcane Yield as a Function of Straw Removal

Two main components explained about 89 to 85% of the total variance of soil attributes and sugarcane yield data under straw removal rates for clayey and sandy soils, respectively (Fig. 7). The results revealed that 72% of the variation in clayey soil was explained by PC1, which was positively correlated with MaP, MiP, MWD, and SOC, and negatively with SRP and BD. The PC2 explained 17% of the variation, showing positive relations with SRP, MaP, MiP, MWD, and BD, and negative with SOC. In sandy loam soils, PC1 explained 71% of

Table 2 Cumulative effects of sugarcane straw removal (NR, no removal; LR, low removal; HR, high removal; and TR, total removal) on soil macroporosity (MaP, $m^3 m^{-3}$) and microporosity (MiP, $m^3 m^{-3}$) in the 0.0–0.05, 0.05–0.10, 0.10–0.20, and 0.20–0.40 m layers in four sites (Clayey 1 and 2 and Sandy 1 and 2)

Straw removal rate	Clayey_1		Clayey_2		Sandy 1		Sandy 2		
	MaP	MiP	MaP	MiP	MaP	MiP	MaP	MiP	
0.0–0.05 m									
NR	0.21ns	0.19ns	0.15b	0.20ns	0.14ns	0.08a	0.17ns	0.07ns	
LR	0.21	0.20	0.16a	0.20	0.13	0.07b	0.17	0.07	
HR	0.19	0.15	0.14b	0.20	0.13	0.07b	0.17	0.07	
TR	0.16	0.18	0.15b	0.20	0.12	0.07b	0.16	0.07	
0.05–0.10 m									
NR	0.21ns	0.20ns	0.17ns	0.23a	0.13a	0.07ns	0.18ns	0.08ns	
LR	0.22	0.20	0.15	0.22ab	0.13a	0.07	0.19	0.08	
HR	0.19	0.16	0.15	0.22ab	0.12b	0.07	0.17	0.07	
TR	0.18	0.14	0.15	0.20b	0.12b	0.07	0.15	0.06	
0.10–0.20 m									
NR	0.22a	0.20ns	0.19a	0.23ns	0.13ns	0.07a	0.15ns	0.06ns	
LR	0.22a	0.21	0.19a	0.23	0.12	0.06ab	0.16	0.06	
HR	0.18b	0.16	0.18b	0.21	0.11	0.06ab	0.14	0.06	
TR	0.19ab	0.16	0.18b	0.22	0.11	0.05b	0.13	0.06	
0.20–0.40 m									
NR	0.22ns	0.21ns	0.18ns	0.25ns	0.12ns	0.08ns	0.14ns	0.07ns	
LR	0.24	0.21	0.18	0.23	0.12	0.07	0.13	0.07	
HR	0.21	0.14	0.18	0.22	0.11	0.07	0.12	0.06	
TR	0.21	0.15	0.17	0.23	0.10	0.07	0.12	0.06	

Means followed by the same letter within columns for each soil layer do not differ among themselves according to Tukey’s test ($p < 0.05$). ns, not significant

the variance, being positively correlated with MaP, MiP, MWD, and SOC, and negatively with SRP and BD. The PC2 explained 14% of the total variation, being positively correlated with SRP, MaP, SOC, MWD, and negatively with BD and MiP. A clear distinction between two clusters was observed in both soil types, in which the HR and TR rates were associated with soil compaction indicators (greater SRP and BD), while LR and NR were associated with greater soil structure conditions (i.e., higher soil porosity, MWD of aggregates, and SOC content).

Discussion

How Does Straw Removal Affect Soil Physical Quality?

Straw maintenance on soil surface supports several processes related to soil physical and hydraulic functions [3]. Increased BD and SRP values observed in all sites confirm that soil compaction was intensified by straw removal. This effect was observed in the top and deepest soil layers (Figs. 1, 2, and 3). Straw layer maintained on soil surface acts as a “damper,” increasing the contact area of machinery wheels with the soil. Thus, part of the load weight on the soil is dissipated, consequently reducing the load transmission in depth [23]. A

recent study showed that from 20 to 40% of straw have not decomposed during a period of 1 year [24], showing that this crop residue layer may function as a soil protection against compaction during the harvesting period. Therefore, the potential effect of remaining straw on load dissipation of harvester traffic may effectively alleviate part of compressive loads from trucks or tractors, and wagons. Our findings also showed that straw removal reduced the soil aggregate stability (Fig. 4), being more significant in sandy soils, where SOC was substantially reduced due to the intensive straw removal under HR and TR treatments (Fig. 5). Soil C plays multiple functions on soil aggregation processes [25], enhancing soil structure and resulting in positive feedbacks on several physical functions and ecosystem services [10, 26]. Therefore, our results confirm that the indiscriminate straw removal for consecutive years leads the soil to a vicious circle, where the reduction of straw-C inputs depletes SOC stocks (Fig. 5), reduces aggregates stability, and consequently leads to a progressive degradation of soil structure. Likewise, poorly structured soil impairs root growth and biological activity, reducing C inputs and their allocation and storage in the soil, further compromising the soil structure and reducing soil resilience to compaction.

Straw mulching also prevents direct impact of raindrops [8]. Thus, both HR and TR increase the susceptibility to

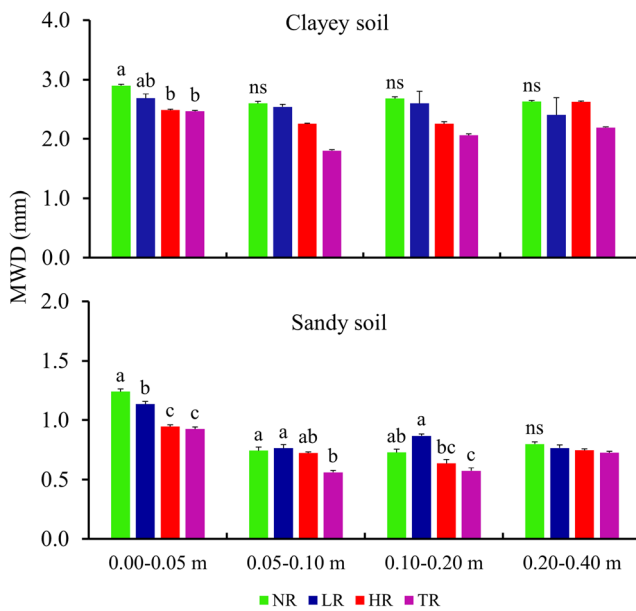


Fig. 4 Cumulative effects of sugarcane straw removal (NR, no removal; LR, low removal; HR, high removal; and TR, total removal) after four sugarcane crops on mean weight diameter (MWD, mm) of aggregates in clayey and sandy soils (Clayey_1 and Sandy_1) in the 0.0–0.05, 0.05–0.10, 0.10–0.20, and 0.20–0.40 m layers. Means followed by the same letter between bars do not differ among themselves according to Turkey test ($p < 0.05$). ns, not significant

surface sealing by disorderly depositing disaggregated soil particles, which reduces soil porosity [27]. Low soil porosity reduces water infiltration and increases surface runoff and soil erosion [28–30]. On the other hand, LR management still

provides high soil cover, protecting the soil surface and minimizing the risks of soil erosion [8, 30]. Soil degradation by erosion has already been identified as a serious threat to the sustainability of the Brazilian sugarcane production [31]. It is imperative to consider that the intensive straw removal can further intensify this problem, and thus we encourage additional studies to evaluate soil erosion and quantify its consequences (i.e., soil, water, SOC, and nutrient losses) induced by straw removal for bioenergy production.

How Are the Effects of Straw Removal on Soils with Different Textures?

In both types of soil, HR and TR were associated with high SRP (> 2.0 MPa) and BD (> 1.6 Mg m⁻³) values. Soil compaction induced by straw removal can limit root exploration and, consequently, the absorption of water and nutrients [32]. For instance, studies conducted by Barbosa et al. [33] suggested that the sugarcane root development was impaired when SRP reached 2.5 and 1.5 Mpa in clayey and sandy soils under field capacity, respectively. As the levels of soil compaction regulate the growth and functionality of sugarcane rooting system, sandy soils can remain stable at first, but resilience is necessary to sustain soil physical functions and prevent irreversible effects. Thus, soils with low stability are more sensitive to straw management [34], which is regularly unable to support higher crop yield, as verified in sandy soils (Fig. 6). On the other hand, the high water holding capacity of

Fig. 5 Cumulative effects of sugarcane straw removal (NR, no removal; LR, low removal; HR, high removal; and TR, total removal) on soil organic carbon concentration (g kg⁻¹) in the 0.0–0.05, 0.05–0.10, 0.10–0.20, and 0.20–0.40 m layers in four sites (Clayey 1 and 2 and Sandy 1 and 2). * indicates significant difference according to Tukey's test ($p < 0.05$). ns, not significant

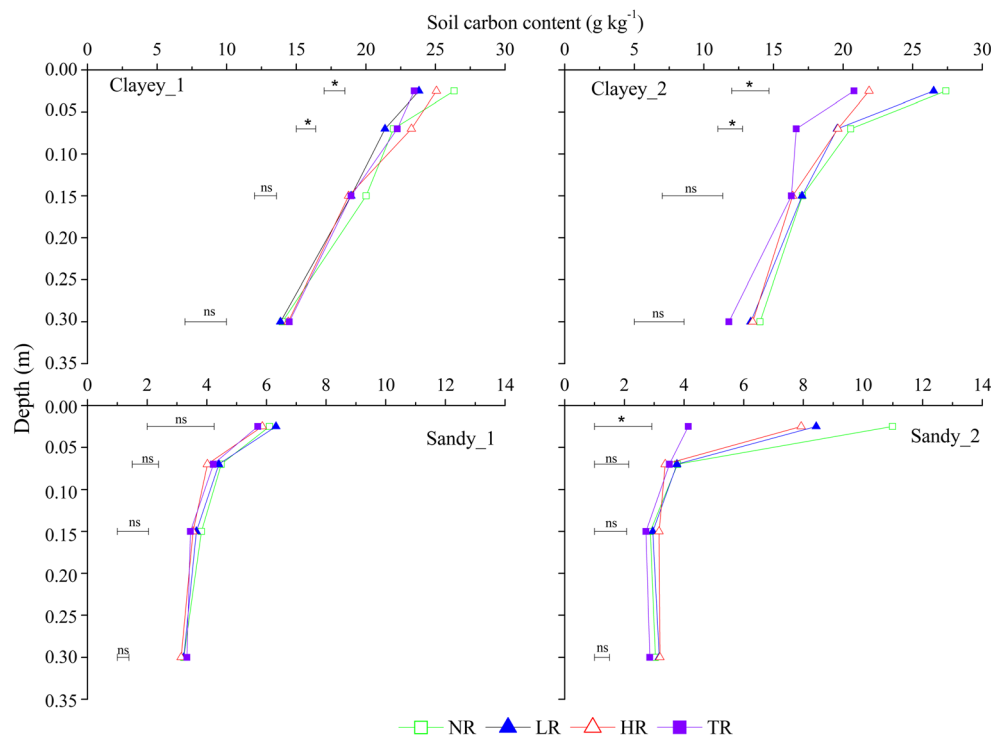
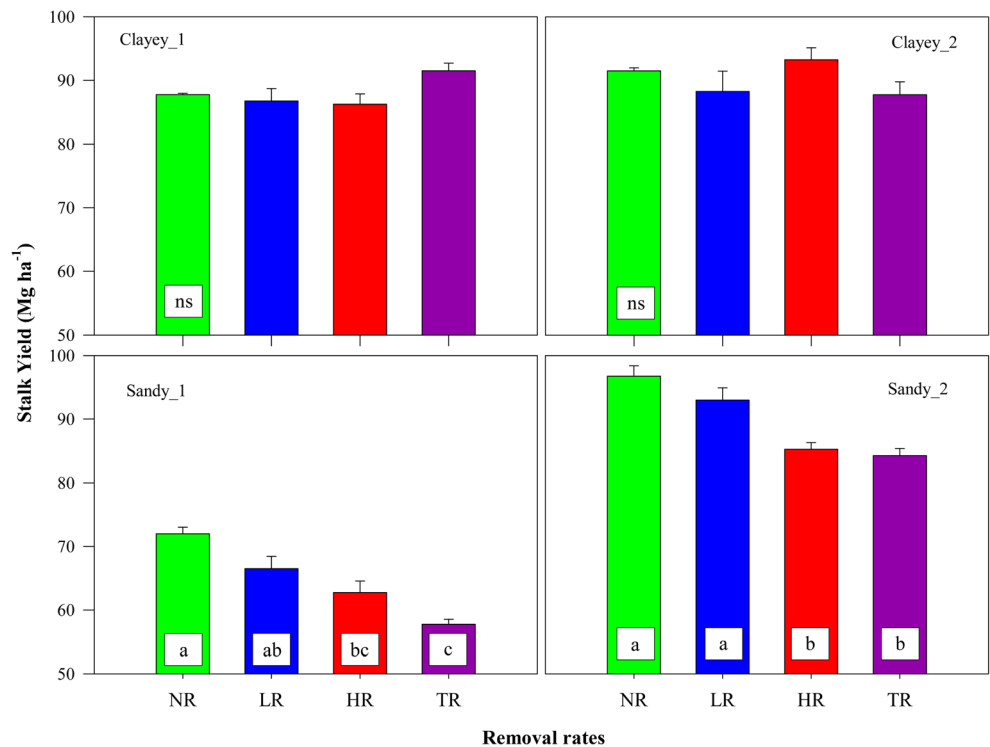


Fig. 6 Sugarcane stalk yield (average yield of four harvests) under different straw removal rates (NR, no removal, LR, lower removal, HR, high removal; and TR, total removal). Means followed by the same letter between bars do not differ from each other, according to Tukey’s test ($p < 0.05$)



clayey soils can increase compaction risks with machinery traffic [35], especially in areas harvested in periods overlapping the rainy season in south-central Brazil.

Indeed, responses from different soil types do not always follow the same pattern (Figs. 3 and 4). The magnitude of the impacts of straw removal on soil physical indicators is associated with the edaphoclimatic conditions and management practices adopted in each location. Recent studies have demonstrated that the adoption of a single guideline for straw removal practices is not feasible in Brazil to ensure soil quality [5, 14, 15]. However, those studies brought important insights concerning the planning and establishment of regionalized

strategies for straw management. Lisboa et al. [14] reported that soil attributes, such as texture and SOC content, are relevant for straw removal planning and management. By applying equal straw removal rates in different regions, our findings revealed that sandy soils can physically degrade faster than clayey soils, indicating that sandy soils are less resistant to bare soil conditions. Moreover, different from what has been observed in this study, straw removal from clayey soils can significantly reduce sugarcane yields in some specific locations [13, 15]. Soil type is an important component on the decision-making for straw removal recommendations, but this factor should be jointly analyzed with other variables. For

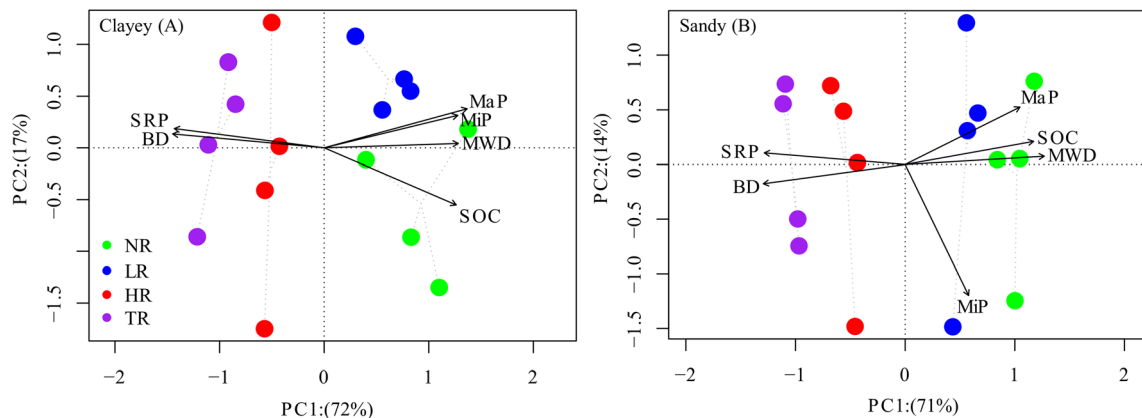


Fig. 7 Relationship between sugarcane stalk yield (variable response) and soil attributes: soil resistance to penetration (SRP), density (BD), macroporosity (MaP), microporosity (MiP), mean weight diameter

(MWD) of soil aggregates and soil carbon content (SOC), in 0.40 m soil profile in clayey and sandy areas under straw removal (NR, no removal; LR, low removal; HR, high removal; and TR, total removal)

example, Carvalho et al. [36] compiled data from 28 field studies and concluded that the best management strategy for straw removal recommendations should take into account information related to local climate conditions, harvesting season, crop aging, and soil type.

Linking Soil Physical Changes Induced by Straw Removal and Sugarcane Yields

Straw removal management alters the soil physical conditions, but the sugarcane yield responses are site-specific and dependent on several factors. Hassuani et al. [37] and Carvalho et al. [36] observed that the effects of straw removal on crop yield are very complex, and in some cases, they can increase, decrease, or produce no effects on sugarcane yields. Currently, the sugarcane yield in Brazil, even in a scenario of no straw removal, has been substantially affected by soil compaction induced by heavy and intensive machinery traffic [38]. Our data show that indiscriminate straw removal gradually reduces SOC stocks (Fig. 5), which in turn can significantly modify soil physical attributes (Figs. 3 and 4), further intensifying soil compaction-related issues in sugarcane fields.

In this study, intensive straw removal (HR and TR) showed close association with higher SRP and BD, being strongly related to lower sugarcane yield (Fig. 7), especially in sandy soils (Fig. 6), corroborating results recently reported in literature [15, 39]. However, soil compaction is not the only factor limiting crop yield in Brazil, where most of the sugarcane yield losses come from climate-related conditions [40]. Carvalho et al. [9] pointed out that the climatic conditions of the south-central region of Brazil, characterized by rainy summers and dry winters, make straw maintenance an important practice for soil moisture and water conservation, thus increasing the water-use efficiency in sugarcane crop. Sugarcane is a semi-perennial crop that goes through several periods of water deficit throughout the year, which can be more significant to plants growing in sandy soils. The water percolation in sandy soils occurs rapidly mainly because they are low aggregated, poorly structured, and present a prevalence of macropores that result in a lower water holding capacity than clayey soils [41]. Accordingly, the straw cover preserves soil moisture in areas under higher water deficit, acting as a physical barrier that reduces water losses by evaporation and enhances soil water storage capacity [42, 43]. This is especially true for sandy soils under high water deficit, where straw cover plays a fundamental role on the sustainability of crop yields [1]. Although presenting low fertility, successive straw inputs to sandy soil can substantially increase nutrient recycling [44], contributing to improve plant nutrition and sugarcane growth [14]. Therefore, straw removals from sandy soils are more likely to cause significant reductions in crop yield than from clayey soils, which are less susceptible to water deficit and present higher soil fertility [45].

It is important to mention that the management of straw removal should consider best management practices to partially attenuate the negative implications on soil physical quality and crop yields [3]. These practices should include the adoption of conservation tillage and crop rotation during sugarcane planting since they increase SOC content and soil structural quality [26]. In addition, as traffic control has emerged as a potential strategy [46], it should come into effect by either using an autopilot [38] or by reducing planting spacing [47]. Hence, the wheel track width should be adjusted to prevent machine traffic over areas intended for plant growth. The preservation of these areas helps reducing the proportion of compacted areas, promoting increased root growth in the soil profile, and, as a consequence, the enhancement of plant yield [33, 38].

Conclusions

Sugarcane straw removal, particularly when associated with total and high removal rates, led to soil organic carbon depletion and soil physical degradation in comparison with low and no removal scenarios. The highest soil compaction (i.e., higher bulk density and soil resistance to penetration) induced by straw removal was strongly associated with lower stalk yields, particularly in sandy soils. In view of the annual straw production of 15 Mg ha^{-1} , our data showed that the low removal rate ($5 \text{ Mg ha}^{-1} \text{ year}^{-1}$) was not detrimental for soil physical quality and sugarcane yield. However, it is important to emphasize that not all of the sugarcane producing regions is able to achieve an annual straw production of 15 Mg ha^{-1} , which was considered in this study to predict a feasible straw production across different Brazilian regions. Therefore, we advocate that the decision-making on straw management needs to be region-oriented, based on crop and soil responses to straw removal according to site-specific characteristics of soil, climate, and crop management. Recommendations for straw removal should also be combined with other conservationist soil management practices in order to minimize soil compaction and its negative implications on sugarcane yield and other ecosystem services.

Acknowledgments We would like to thank LNBR technicians' group for all the support in the field and laboratory activities, and the Quatá and Boa Vista Mills for providing the experimental sites and the logistical support during fieldwork.

Funding Information This research was supported by the Sugarcane Renewable Electricity project—SUCRE/PNUD (grant number BRA/10/G31) and the National Council for Scientific and Technological Development—CNPq (grant number 406922/2013-6). We are grateful to the Agrisus Foundation (grant number 2563/18) and the São Paulo Research Foundation—FAPESP for providing the research grants (grant numbers 2017/23978-7 and 2018/09845-7).

Compliance with Ethical Standards

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

References

- Bordonal RO, Carvalho JLN, Lal R, Figueiredo EB, Oliveira BG, La Scala N Jr (2018a) Sustainability of sugarcane production in Brazil. A review. *Agron Sustain Dev* 38:13. <https://doi.org/10.1007/s13593-018-0490-x>
- Menandro LMS, Cantarella H, Franco HCJ, Kölln OT, Pimenta MTB, Sanches GM, Rabelo SC, Carvalho JLN (2017) Comprehensive assessment of sugarcane straw: implications for biomass and bioenergy production. *Biofuels Bioprod Biorefin* 11: 488–504. <https://doi.org/10.1002/bbb.1760>
- Cherubin MR, Oliveira DMS, Feigl BJ, Pimentel LG, Lisboa IP, Gmach MR, Varanda LL, Moraes MC, Satiro LS, Popin GV, Paiva SR, Santos AKB, Vasconcelos ALS, Melo PLA, Cerri CEP, Cerri CC (2018) Crop residue harvest for bioenergy production and its implications: a review. *Sci Agric* 75:255–272. <https://doi.org/10.1590/1678-992x-2016-0459>
- Castioni GA, Cherubin MR, Menandro LMS, Sanches GM, Bordonal RO, Barbosa LC, Carvalho JLN (2018) Soil physical quality response to sugarcane straw removal in Brazil: a multi-approach assessment. *Soil Tillage Res* 184:301–309. <https://doi.org/10.1016/j.still.2018.08.007>
- Satiro LS, Cherubin MR, Safanelli JL, Lisboa IP, da Rocha PR Jr, Cerri CEP, Cerri CC (2017) Sugarcane straw removal effects on ultisols and oxisols in south-central Brazil. *Geoderma Reg* 11:86–95. <https://doi.org/10.1016/j.geodrs.2017.10.005>
- Blanco-Canqui H, Lal R (2009) Crop residue removal impacts on soil productivity and environmental quality. *Crit Rev Plant Sci* 28: 139–163. <https://doi.org/10.1080/07352680902776507>
- Pulido M, Penning HL, Timm CL, Gabriels D, Cornelis WM (2014) Visual examinations and soil physical and hydraulic properties for assessing soil structural quality of soils with contrasting textures and land uses. *Soil Tillage Res* 140:20–28. <https://doi.org/10.1016/j.still.2014.02.009>
- Martins Filho MV, Licciotti TT, Pereira GT, Marques Junior J, Sanches RB (2009) Perdas de solo e nutrientes por erosão num Argissolo com resíduos vegetais de cana-de-açúcar. *Eng Agríc* 29:8–18. <https://doi.org/10.1590/S0100-69162009000100002>
- Carvalho JLN, Nogueirol RC, Menandro LMS, Bordonal RO, Borges CD, Cantarella H, Franco HCJ (2017) Agronomic and environmental implications of sugarcane straw removal: a major review. *Glob Change Biol Bioenergy* 9:1181–1195. <https://doi.org/10.1111/gcbb.12410>
- Rabot E, Wiesmeier M, Schlüter S, Vogel HJ (2018) Soil structure as an indicator of soil functions: a review. *Geoderma* 314:122–137. <https://doi.org/10.1016/j.geoderma.2017.11.009>
- Vischi Filho OJ, Souza ZM, Da Silva RB, Lima CC, Pereira DMG, de Lima ME, Sousa AC, Souza GS (2015) Capacidade de suporte de carga de Latossolo Vermelho cultivado com cana-de-açúcar e efeitos da mecanização no solo. *Pesq Agrop Brasileira* 50:322–332. <https://doi.org/10.1590/S0100-204X2015000400008>
- Benazzi ES, Bianchi MO, Correia MEF, Lima E, Zonta E (2013) Impactos dos métodos de colheita da cana-de-açúcar sobre a macrofauna do solo em área de produção no Espírito Santo—Brasil. Impacts of harvesting methods of sugar cane on the soil macrofauna in production area in Espírito Santo—Brazil. *Semina Cienc Agrár* 34:3425–3442. <https://doi.org/10.5433/1679-0359.2013v34n6Supl1p3425>
- Aquino GS, Medina CC, Costa DC, Shahab M, Santiago AD (2017) Sugarcane straw management and its impact on production and development of ratoons. *Ind Crop Prod* 102:58–64. <https://doi.org/10.1016/j.indcrop.2017.03.018>
- Lisboa IP, Cherubin MR, Satiro LS, Siqueira-Neto M, Lima RP, Gmach MR, Gmach MR, Wienhold BJ, Schmer MR, Jin VL, Cerri CC, Cerri CEP (2019) Applying soil management assessment framework (SMAF) on short-term sugarcane straw removal in Brazil. *Ind Crop Prod* 129:175–184. <https://doi.org/10.1016/j.indcrop.2018.12.004>
- Bordonal R de O, Menandro LMS, Barbosa LC, Rattan L, Milori DMBP, Kölln OT, Franco HCJ, Carvalho JLN (2018b) 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>
- Alvares CA, Stape JL, Sentelhas PC, Gonçalves JLM, Sparovek G (2013) Köppen's climate classification map for Brazil. *Meteorol Z* 22:711–728. <https://doi.org/10.1127/0941-2948/2013/0507>
- Soil Survey Staff (2014) Keys to soil taxonomy, 12th edn. USDA - natural resources conservation service, Washington, DC 360 pp
- van RB, Andrade JC, Cantarella H, Quaggio JA (2001) Análise química para avaliação da fertilidade do solos tropicais. Instituto Agronômico, Campinas 285p
- Teixeira PC, Donagemma GK, Fontana AI, Teixeira WG (2017) Manual de métodos de análise de solo. EMBRAPA Solos, 3rd edn. Brasília, DF, Brasil.
- Imhoff S, Kay BD, Pires A, Hajabbasi MA (2010) Evaluating responses of maize (*Zea mays* L.) to soil physical conditions using a boundary line approach. *Soil Tillage Res* 106:303–310
- Kemper W, Chepil W (1965) Size distribution of aggregates. In: Black C (ed) American Society Agronomy, 9th edn. Methods of soil analysis, Madison, pp 499–510
- R Development Core Team (2015) R: a Language and Environment for Statistical Computing, R Found. Stat. Comput., Vienna, Austria. <http://www.R-project.org>
- Reichert JM, Brandt AA, Rodrigues MF, Reinert DJ, Braida JA (2016) Load dissipation by corn residue on tilled soil in laboratory and field-wheeling conditions. *J Sci Food Agric* 96:2705–2714. <https://doi.org/10.1002/jsfa.7389>
- Varanda LL, Cherubin MR, Cerri CEP (2019) Decomposition dynamics altered by straw removal management the sugarcane-expansion regions in Brasil. *Soil Res* 57:41–52. <https://doi.org/10.1071/SR17298>
- Tisdall JM, Oades JM (1982) Organic matter and water-stable aggregates in soils. *Soil Sci* 33:141–163. <https://doi.org/10.1111/j.1365-2389.1982.tb01755.x>
- Cherubin MR, Franco ALC, Guimarães RML, Tormena CA, Cerri CEP, Karlen DL, Cerri CC (2017) Assessing soil structural quality under Brazilian sugarcane expansion areas using visual evaluation of soil structure (VESS). *Soil Tillage Res* 173:64–74. <https://doi.org/10.1016/j.still.2016.05.004>
- Dalla Rosa J, Cooper M, Darboux F, Medeiros JC, Campanaro C, Pinto LRM (2012) Soil roughness evolution in different tillage systems under simulated rainfall using a semivariogram-based index. *Soil Tillage Res* 124:226–232. <https://doi.org/10.1016/j.still.2012.06.001>
- Bielders CL, Grymonprez B (2010) Raindrop impact: a neglected but potentially major contributor to particle mobilization in soils. *Soil Sci Soc Am J* 74:1446–1456. <https://doi.org/10.2136/sssaj2009.0245>
- Johnson JMF, Strock JS, Tallaksen JE, Reese M (2016) Corn stover harvest changes soil hydrology and soil aggregation. *Soil Tillage Res* 161:106–115. <https://doi.org/10.1016/j.still.2016.04.004>
- Valim WC, Panachiki E, Pavei DS, Alves Sobrinho T, Almeida WS (2016) Effect of sugarcane waste in the control of interrill erosion.

- Semina Ciênc Agrár 37:1155–1164. <https://doi.org/10.5433/1679-0359.2016v37n3p1155>
31. Filoso S, Carmo JB, Mardegan SF, Lins SR, Gomes TF, Martinelli LA (2015) Reassessing the environmental impacts of sugarcane ethanol production in Brazil to help meet sustainability goals. *Renew Sust Energ Rev* 52:1847–1856. <https://doi.org/10.1016/j.rser.2015.08.012>
 32. Reichert JM, Reinert DJ, Braida JA (2003) Qualidade dos solos e sustentabilidade de sistemas agrícolas. *Ciência e Ambiente* 27:29–48
 33. Barbosa LC, de Souza ZM, Franco HCJ, Otto R, Rossi Neto J, Garside AL, Carvalho JLN (2018) Soil texture affects root penetration in Oxisols under sugarcane in Brazil. *Geoderma Reg* 13:15–25. <https://doi.org/10.1016/j.geodrs.2018.03.002>
 34. Gregory AS, Watts CW, Whalley WR, Kuan HL, Griffiths BS, Hallet PD, Whitmore AP (2007) Physical resilience of soil to field compaction and the interactions with plant growth and microbial community structure. *Eur J Soil Sci* 58:1221–1232. <https://doi.org/10.1111/j.1365-2389.2007.00956.x>
 35. Shah AN, Tanveer M, Shahzad B, Yang G, Fahad S, Bukhari MA, Tung SA, Hafeez A, Souliyanonh B (2017) Soil compaction effects on soil health and crop productivity: an overview. *Environ Sci Pollut Res Int* 11:1056–1067. <https://doi.org/10.1007/s11356-017-8421-y>
 36. Carvalho JLN, Menandro LMS, Castro SGQ, Cherubin MR, Bordonal RO, Barbosa LC, Gonzaga LC, Tenelli S, Franco HCJ, Kolln OT, Castioni GAF (2019) Multilocation straw removal effects on sugarcane yield in south-central Brazil. (*Sugar*) of *BioEnergy Research*
 37. Hassuani SJ, Leal MRLV, Macedo IC (2005) Biomass power generation: sugar cane, bagasse and trash. Programa das Nações Unidas para o Desenvolvimento (PNUD), Centro de Tecnologia Canavieira (CTC), Piracicaba, SP, Brasil.
 38. Esteban DA, Souza ZM, Tormena CA, Lovera LH, Lima ES, Oliveira IN, Ribeiro NP (2019) Soil compaction, root system and productivity of sugarcane under different row spacing and controlled traffic at harvest. *Soil Tillage Res* 187:60–71. <https://doi.org/10.1016/j.still.2018.11.015>
 39. Satiro LS, Cherubin MR, Lisboa IP, Noia Junior RS, Cerri CC, Cerri CEP (2018) Prediction of sugarcane yield by soil attributes under straw removal management. *Agron J* 110:1–10
 40. Dias HB, Sentelhas PC (2018) Sugarcane yield gap analysis in Brazil - a multi model approach for determining magnitudes and causes. *Sci Total Environ* 638:1127–1136. <https://doi.org/10.1016/j.scitotenv.2018.05.017>
 41. Corrêa STR, Scarpore FV, Barbosa LC, Menandro LM, Reichardt K, Moraes LO, Franco HCJ, Hernandez TAD, Carvalho JLN (2019) Straw removal effects on soil water dynamics, soil temperature and sugarcane yield in south-central Brazil. *Bioenergy Res*. <https://doi.org/10.1007/s12155-019-09981-w>
 42. Chen SY, Zhang XY, Pei D, Sun HY, Chen SL (2007) Effects of straw mulching on soil temperature, evaporation and yield of winter wheat: field experiments on the North China Plain. *Ann Appl Biol* 150:261–268. <https://doi.org/10.1111/j.1744-7348.2007.00144.x>
 43. Scopel E, Macena F, Corbeels M et al (2004) Modelling crop residue mulching effects on water use and production of maize under semi-arid and humid tropical conditions. *Agronomie* 24:1–13. <https://doi.org/10.1051/agro:2004029>
 44. Trivelin PCO, Franco HCJ, Otto R, Ferreira DA, Vitti AC, Fortes C, Faroni CE, Oliveira EC, Cantarella H (2013) Impact of sugarcane trash on fertilizer requirements for São Paulo, Brazil. *Sci Agric* 70: 345–352
 45. Costa MC, Mazza JA, Vitti GC, Jorge LAC (2007) Distribuição radicular, estado nutricional e produção de colmos e de açúcar em soqueiras de dois cultivares de cana-de-açúcar em solos distintos. *Rev Bras Ciênc Solo* 31:1503–1514. <https://doi.org/10.1590/S0100-06832007000600027>
 46. Braunack MV, McGarry D (2006) Traffic control and tillage strategies for harvesting and planting of sugarcane (*Saccharum officinarum*) in Australia. *Soil Tillage Res* 89:86–102. <https://doi.org/10.1016/j.still.2005.07.002>
 47. Rossi Neto J, de Souza ZM, Kölln OT, Carvalho JLN, Ferreira DA, Castioni GAF, Barbosa LC, Castro SGQ, Braunbeck AO, Garside AL, Franco HJC (2018) The arrangement and spacing of sugarcane planting influence root distribution and crop yield. *Bioenergy Res* 11:291–304. <https://doi.org/10.1007/s12155-018-9896-1>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.