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Soil dissolved organic carbon responses to sugarcane straw removal

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Abstract

Global demand for bioenergy increases interest in biomass-derived fuels, as ethanol from sugarcane straw. However, straw is the main carbon source to soil and its removal reduces C input, affecting active fractions (dissolved organic carbon, DOC) and C storage. To quantify the effects of straw removal on DOC and C stocks, we built lysimeter system using soil (Rhodic Kandiudox) from sugarcane field. We evaluated four soil depths (1, 20, 50 and 100 cm) and four straw removal rates: no removal NR, medium MR, high HR and total TR, leaving 12, 6, 3 and 0 Mg/ha on the soil surface, respectively. After rainfall, drainage water was collected and analysed for DOC content. Soil C stocks were determined after the 17-month. Total DOC released at 1-cm depth amounted to 606, 500, 441 and 157 kg/ha in NR, MR, HR and TR, respectively. Net-DOC suggests straw as the main source of DOC. Most of DOC in NR (50%) was retained within the 1–20 cm layer, resulting in higher C stock (10 Mg/ha) in the topsoil. In HR and MR, DOC retention was higher within 20–50 cm, suggesting differences in DOC composition. DOC in TR was 40% higher at 20 cm than at 1 cm, indicating C losses from topsoil. Low concentrations of DOC were found at 100-cm depth, but representing 30% in TR. Straw removal for bioenergy production is sustainable, but we should leave at least 3 Mg/ha of straw to ensure DOC production and soil C storage, taking account the DOC contribution to key soil functions.

KEYWORDS

crop management, soil carbon storage, soil organic matter, tropical soils

1 | INTRODUCTION

Biomass energy is increasing worldwide as a strategy to reduce greenhouse gas emissions, mitigating climate change (IPCC, 2019). In Brazil, which has major sugarcane-based ethanol production, an area of 8.5 million ha is devoted to sugarcane production, with 630 million tons of cane harvested annually (2018/19 season; CONAB, 2019). This yields more than 30 billion litres of bioethanol (30% of global supply) and more 20 TWh of bioelectricity by co-generation (10% of national demand) (UNICA, 2019).

The sugarcane crop produces large amounts of cellulosic biomass comprising leaves and tops (10–20 Mg/ha dry matter) (Leal et al., 2013), which are left in the field (crop residues/straw) after cane harvest. Cellulosic materials are considered promising feedstock for increasing the supply of low-intensity carbon (C) biofuel (e.g. second-generation ethanol, E2G), with great potential to replace fossil-derived fuels (Ojeda et al., 2011). Therefore, interest in using straw for bioenergy purposes has increased substantially in recent years (Menandro et al., 2017).

However, straw is the main C input to sugarcane fields (Carvalho et al., 2013) and thus has a critical function in sustaining soil health (Cherubin et al., 2018; Lisboa et al., 2019). Therefore, depending on the intensity, straw removal can pose a potential threat to the sustainability of sugarcane production (Blanco-Canqui & Lal, 2009; Carvalho et al., 2017; Cherubin et al., 2018).

Crop residues are a potential resource for improving soil C sequestration (Villamil et al., 2015). Total soil organic carbon (SOC) is relatively unaffected by soil management practices in the short term (Haynes, 2000), but labile organic C fractions are known to be rapid indicators of changes in SOC pools affected by management practices (Blanco-Moure et al., 2016). Dissolved organic carbon (DOC) is one of the most mobile and bioavailable soil organic C compounds (Marschner & Kalbitz, 2003). It is important for nutrient cycling and distribution (Veum et al., 2009), as an energy source for microbial activity (De Troyer et al., 2011), and in organic-metallic complexation (Franchini et al., 2003). In addition, DOC is a substantial component of the net C balance of ecosystems (Kindler et al., 2011).

Plant residues and soil organic matter (SOM) mineralization are the main DOC sources in the soil (Fröberg et al., 2003; Michalzik et al., 2003; Zsolnay, 1996). The DOC production rate varies depending on the quantity and quality of plant (crop) residues (Kalbitz et al., 2000), soil type, climate (Kalbitz & Knappe, 1997), and land use and management (Gregorich et al., 2000; Leinweber et al., 2008; Sousa Junior et al., 2018). As its major sources are more concentrated in the topsoil, the DOC concentration is greater at the soil surface and decreases with depth in the soil (Gregorich et al., 2000; Hassan et al., 2016; McDowell & Likens, 1988). DOC adsorption to soil minerals, such as clays and iron (Fe) and aluminium (Al) oxides, is also higher at the soil surface (Kaiser et al., 1996; Kalbitz et al., 2000). Nevertheless, due to its mobility, DOC plays an important role in C redistribution within the soil profile and is the main C source to deeper soil layers (Fröberg et al., 2007; Kalbitz & Kaiser, 2008; Sparling et al., 2016). It can also be leached beyond rooting depth and transferred to aquatic systems (Sparling et al., 2016).

Brazil has great potential to expand its energy matrix from biomass, mainly using sugarcane straw. However, the impacts of straw removal on the DOC fraction are still not well-explored (Sousa Junior et al., 2018), leaving unanswered questions relating to DOC production, retention, and losses, and changes in soil C storage in sugarcane fields (Gmach et al., 2020). The hypothesis tested in the present study was that sugarcane straw is the main source of DOC release in the soil and therefore, by removing high rates of sugarcane straw from the soil surface reduces production of DOC and consequently its percolation within the soil profile, consequently reducing soil C storage. To test this hypothesis, we constructed free-draining soil lysimeters and established them at a field site in São Paulo state, Brazil, to evaluate changes in DOC production, retention, and losses, and changes in soil C storage due to straw removal over two sugarcane harvests.

2 | MATERIAL AND METHODS

2.1 | Experimental set-up and environmental conditions

A set of free-draining lysimeters (soil columns) were built using a PVC tubes with 5-mm walls, diameter 20 cm and length 1, 20, 50, and 100 cm of soil. The 1-cm soil column was used to allow interaction between straw and soil microorganisms, in order to quantify DOC production from sugarcane straw. At the field site, the lysimeters were placed with their upper edges 1.5 m above ground level and suspended from a steel frame. Perforated stainless-steel plates of 2-mm thickness and 125-μm mesh were fitted to the bottom of the lysimeters, to prevent soil losses. A funnel was attached beneath, with a rubber ring to ensure a tight fit, and connected to a glass bottle by a hose to collect drainage water (for full details see Figure S1, and Gmach et al., 2019).

The lysimeters were filled with soil from a commercial sugarcane field. This soil is classified as a Rhodic Kandiudox (Soil Survey Staff, 2014), with a sandy clay loam texture (600, 70 and 330 g/kg of sand, silt and clay, respectively). It represents a predominant soil type used for sugarcane cultivation in the study region (Demattê & Demattê, 2009). Oxisols and Ultisols dominate in central-southern Brazil (IBGE, 2018), which hosts 90% of national sugarcane production (CONAB, 2019). The soil chemical characterization for the 0–30 cm layer was: cation exchange capacity 6.5 $cmol_c/kg$, pH_{water} 5.0, base saturation 53%, 19.2, 5.5 and 5.9 $mmol_c/dm^3$ calcium (Ca), magnesium (Mg) and potassium (K), respectively, and 25.4 mg/dm^3 phosphorus (P) (Satiro et al., 2018). Soil bulk density was 1.32, 1.37 and 1.38 Mg/m^3 and soil C stock was 16.4, 14.8 and 13.2 Mg/ha in the 0–10, 10–20 and 20–30 cm layers, respectively. The soil had a high Fe and Al oxide content (details in Table S1 (SI)).

The soil columns were assembled by a destructive method, by repacking layers with a rubber mallet applied to the wall of the tubes to try to replicate the field soil bulk density in- every 10 cm layer from 0–10 cm to 90–100 cm. We tried to reconstitute soil within the lysimeter with the original soil layers, keeping the original biota. After construction, the lysimeters were exposed to natural rainfall events for two weeks (~220 mm) to stabilize the soil and minimize potential soil shrinkage before adding the straw treatments.

The lysimeter system was set up in an open field in the municipality of Piracicaba, São Paulo State (22°43′31″S, 47°38′57″W, 547 m alt.) far from possible interferences with rainwater input. The experiment was run for 17 months, comprising two summer periods (i.e. two sugarcane harvests). The first sampling period ran from January to November 2016 and the second from November 2016 to May 2017. The climate in the region is classified as subtropical, with dry winters and hot summers (*Cwa* in the Köppen classification; Alvares et al., 2013). Mean annual rainfall is 1,300 mm, and mean air temperature is 23°C, with temperatures above 35°C in summer and no lower than 10°C in winter.

2.2 | Experimental design and treatments

The experiment had a completely randomized design, with four treatments and four replicates. The four treatments simulated different straw removal rates: (a) no removal (NR), 12 Mg/ha of dry matter (DM) left on soil surface; (b) medium removal (MR), 6 Mg/ha DM left on soil surface; (c) high removal (HR), 3 Mg/ha DM left on soil surface; and (d) total removal (TR), no straw left on soil surface (bare soil). Chopped sugarcane (cultivar SP80-3280) straw from mechanical harvesting was collected from a commercial field, and samples were brought to the laboratory to determine the water content. The straw was composed of approximately 40% top and green leaves and 60% bottom and dry leaves in a heterogeneous shredded mixture, with pieces ranging in size from 1 to 20 cm (Vasconcelos et al., 2018). The straw was weighed, placed on the open top of the lysimeter tubes in contact with the total surface and held in place with a metal grid. The first straw addition was in January 2016 (first sampling period). The lysimeters were kept free of plants throughout the experiment, to evaluate the individual effects of straw on soil organic C.

In November 2016, the remaining straw on the top of the lysimeters was weighed and small samples were taken for determination of dry matter (DM) losses. The straw was then returned to the soil, and a new portion of chopped straw mass, in an amount based on the treatment selected, was placed on top, simulating the second harvest (second sampling period). At the end of the second period (end of May 2017), the total amount of straw remaining on the soil surface was manually collected, as described by Pimentel et al. (2019). The straw was weighed and dried to quantify DM losses. The DM results were corrected for ash content, to exclude contamination by soil. Straw ash content was determined for each treatment by calcining 1 g of straw DM in a muffle furnace at 550°C for 2 hr (Varanda et al., 2019; Vasconcelos et al., 2018).

2.3 | Sample collection and analyses

Throughout the experimental period, after all rainfall events the drainage water from each lysimeter was collected and quantified using a graduated cylinder. Depending on rainfall intensity, water collection lasted for up to four days. The drainage water was passed through a 0.45-μm cellulose nitrate membrane filter and analysed for DOC using an automatic analyser Shimadzu© TOC-VCPN® (Kyoto, Japan). The DOC flux was calculated by multiplying the DOC concentration by the volume of drainage water collected (Sparling et al., 2016). The DOC retention between layers was calculated as the difference in DOC flux between soil columns of different lengths, for example, DOC retention in the 1–20 cm layer was calculated as DOC flux at 1-cm depth minus DOC flux at 20-cm depth).

At the end of the 17-month experimental period, the 100 cm soil column was sampled at different depths (0–5, 5–10, 10–20, 20–30, 30–40, 40–50, 50–60, 60–70, 70–80, 80–90 and 90–100 cm). In each layer, undisturbed soil samples were collected using a volumetric ring (~100 cm^{-3}) and oven-dried for 48 hr. Bulk density was calculated by dividing the mass of dry soil by the ring volume. Sub-samples of soil (~10 g, four replicates) were ground to fine powder, and organic C content was determined by dry combustion using a TrusPec® analyser (LECO©, St. Joseph, USA). Soil C stock (Mg/ha) was calculated as:

$$\text{C stock} = \text{C} \times \text{BD} \times \text{D} \tag{1}$$

where C is the carbon concentration (%), BD is soil bulk density (Mg/m^3), and D is the depth of the soil layer (m).

2.4 | Data analysis

Analysis of variance (ANOVA) was performed to test the effects of straw removal rates on DOC flux and soil C stock. When a significant effect (F-test; $p < .05$) was revealed by ANOVA, the average values were compared using Tukey's test ($p < .05$). Pearson correlation was also calculated to test for correlations between DOC concentrations and straw-C loss. All statistical analyses were performed using the "R" Foundation for Statistical Computing v.3.6.1 software.

3 | RESULTS

3.1 | Precipitation and soil drained water

During the entire 17-month experimental period, 149 days with precipitation were recorded and produced a total of 2,127 mm, of which 1,005 mm fell during the first sampling period (January–November 2016) and 1,122 mm during the second sampling period (mid-November 2016 to May 2017). Both summer seasons (December–March) were quite rainy, with several days of intense rainfall (Figure 1i). In the dry period (May–September), few rainfall events occurred, although in

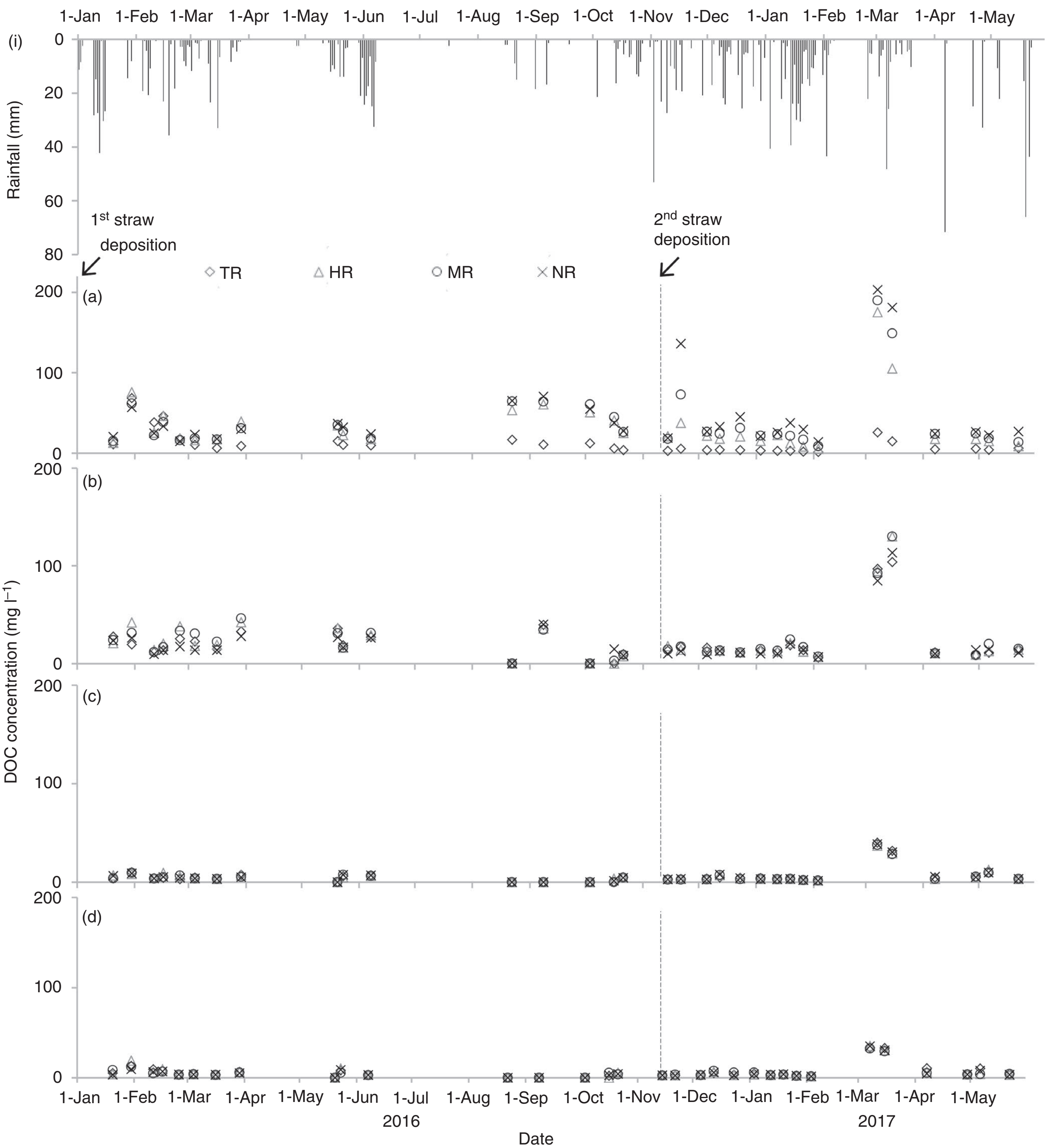

FIGURE 1 Daily precipitation (i; mm) and daily DOC concentration (mg/L) in the drainage water throughout the 17 months (January 2016 to May 2017), with two straw addition indicated by vertical dashed lines, under different sugarcane straw removal rates from the soil surface, in four different soil depths, in which (a) DOC concentration at 1-cm depth; (b) DOC concentration at 20-cm; (c) DOC concentration at 50-cm; and (d) DOC concentration at 100-cm depth. TR, total removal (0 Mg/ha left on soil surface); HR, high removal (3 Mg/ha); MR, medium removal (6 Mg/ha); NR, no removal (12 Mg/ha)

June 2016 an unusually heavy rain event (in total 162 mm) occurred over one week. The total amount of water draining from the lysimeters over the experimental period was greater from the soils with more straw left in place, disregarding the 1-cm soil layer (Table S2).

3.2 | DOC release from topsoil and straw

Higher DOC concentrations were found in drainage water from 1-cm depth (Figure 1a) than in water from deeper soil layers (i.e. 20, 50 or 100 cm), except in treatment TR. After more intense rainfall events, the DOC concentrations in drainage water were reduced, except after heavy rain following dry periods, resulting in elevated soil C concentrations (see June 2016, March 2017; Figure 1).

In TR, DOC flux in drainage water collected at 1-cm depth was only 25%–35% of that observed in treatments with straw (HR, MR and NR; Table 1). Overall, DOC flux was higher with reduced straw removal rate. However, the DOC increment did not follow a linear relationship with straw amount left on the soil surface, since the accumulated net-DOC straw-derived flux for the MR and HR treatments was 23 and 36% lower, respectively, than for the NR treatment ($p < .05$) (Table 1).

3.3 | DOC translocation and retention

DOC concentration in drainage water decreased with increasing soil depth ($p < .05$) (Figures 1 and 2). The exception was TR, in which DOC concentration and DOC flux were higher from the 20-cm depth than the 1 cm (Figure 2; Table 1). At 20-cm depth, the differences in DOC concentration between treatments became less distinct. In water draining from this soil layer, the DOC concentration was higher for MR and HR during several rain events (Figure 1b), and overall (Figure 2; Table 1). DOC retention in the 1–20 cm soil layer was greater with decreasing straw removal rate (Table 1), corresponding to ~ 50% of total DOC released to the topsoil in NR.

For the 50 cm soil depth, DOC concentration declined (Figures 1c and 2), and the differences between treatments became less detectable. The associated DOC retention caused similar cumulative DOC fluxes for all treatments with straw addition, differing only for TR ($p < .05$) (Table 1). For the treatments with straw addition, DOC retention in the 1–50 cm soil layer was 518, 418 and 362 kg/ha in NR, MR and HR, respectively, corresponding to ~84% of total DOC released from the top 1-cm depth. In TR, the 20–50 cm layer retained 70% of DOC released from the 20-cm depth.

The total DOC fluxes at 100-cm depth were slightly smaller than at 50-cm depth, indicating small additional DOC retention in the 50–100 cm soil layer (Table 1), with a contribution of less than 3% for all treatments. Total DOC retention between 1 and 100 cm was ~ 85% for the treatments with straw addition. Consequently, less than 15% of total DOC was transported below 100-cm depth in the treatments with straw addition, while the corresponding value was 30% in TR. However, the difference in DOC leaching between the soil receiving no straw and that with the highest straw application was less than 12 kg C ha^{-1}.

3.4 | DOC release from straw and soil C storage

Straw-C loss by decomposition after the first straw addition differed between the treatments, being higher with decreasing

TABLE 1 Total dissolved organic carbon (DOC) fluxes (kg/ha) and DOC retention (kg/ha) evaluated throughout the soil profile in soil columns at 1-, 20-, 50- and 100-cm depth of different sugarcane straw removal rates from the soil surface after 17 months and two straw addition. Tukey's test and standard deviation were performed to compare treatment means within each soil depth

	Total removal	High removal	Medium removal	No removal
Soil depth (cm)	**Total DOC release in 17 months[b], kg/ha (net-DOC straw-derived, kg/ha)[c]**			
1	157 ± 5.3 c[a]	441 ± 41 b (284)	500 ± 21 b (343)	606 ± 35 a (449)
20	221 ± 22 c	314 ± 31 ab (93)	351 ± 21 a (130)	294 ± 29 b (73)
50	67 ± 1.4 b	80 ± 1.2 a (13)	81 ± 7.4 a (14)	88 ± 2.6 a (21)
100	65 ± 5.3 b	73 ± 2.7 ab (8)	70 ± 3.1 ab (5)	77 ± 4.9 a (12)
	DOC retention in 17 months, kg/ha			
1–20	−64	127	149	312
20–50	154	235	269	206
50–100	2	7	11	11
1–100	92	368	429	529

[a]Mean values followed by the same letter within soil depth did not differ according to Tukey's test ($p < .05$).

[b]17 months of experiment encompassed two straw deposition/or removal (one in time 0 and the second after 11 months).

[c]Net-DOC straw-derived: DOC flux from soil with straw addition—DOC flux from bare soil (TR).

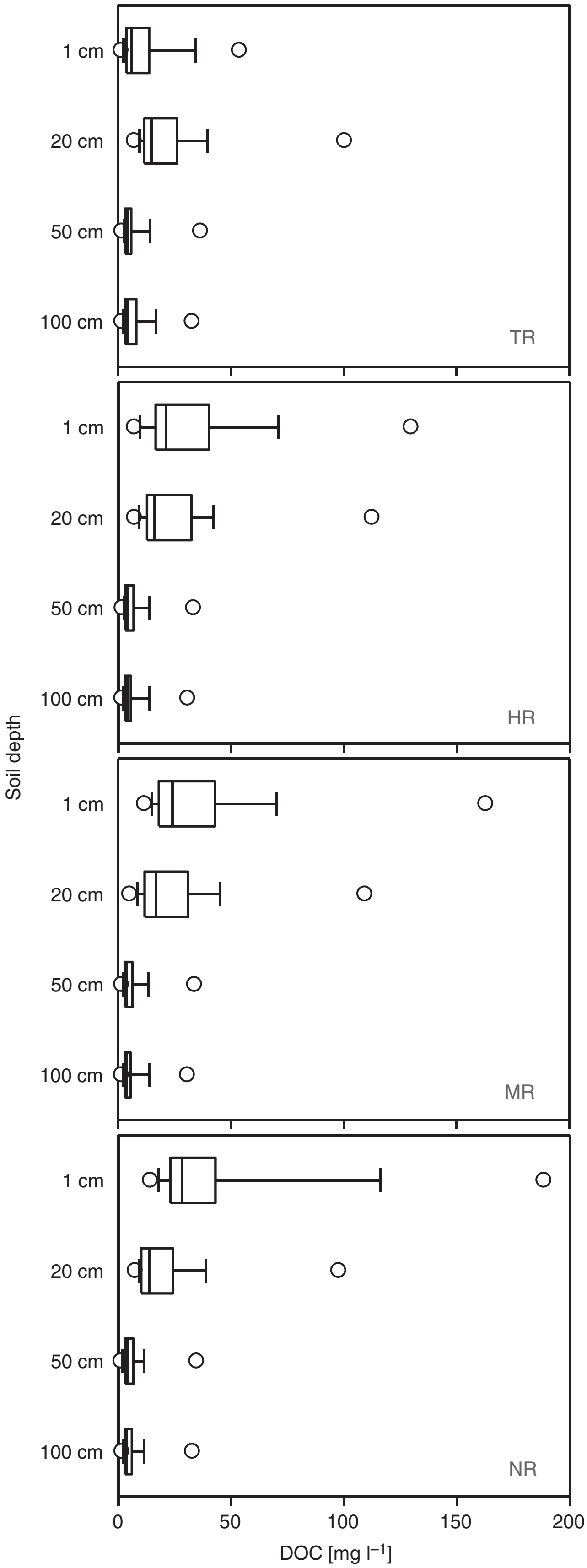

FIGURE 2 Distribution of average dissolved organic carbon (DOC) concentration (mg/L) in drainage water along the soil profile during 17 months (January 2016 to May 2017) and two straw addition, in different sugarcane straw removal rates from the soil surface. The extents of the box indicate 25th and 75th percentiles, and the lines inside the box represent the 50th percentile. Whiskers represent the 10th and 90th percentiles and outliers are given as open symbols. TR: total removal (0 Mg/ha left on soil surface); HR, high removal (3 Mg/ha); MR, medium removal (6 Mg/ha); NR, no removal (12 Mg/ha)

straw removal rate (Table 2). After the second straw addition, the rates of straw-C loss were similar for all treatments. The DOC release at 1-cm depth showed a strong positive correlation with straw-C loss at the soil surface ($r = 0.904$; $p < .05$).

Calculation of the relationship between net-DOC straw-derived release at 1-cm depth (Table 1) and total C loss by straw decomposition (i.e. net-DOC straw-derived/total straw-C lost by decomposition) showed that 16, 9 and 6% of all C lost became DOC in HR, MR and NR, respectively (Table 2). Proportionally, the greater the straw amount left on the soil surface, the less straw-C was recovered as DOC fraction.

At the end of the experimental period, soil C stocks displayed significant differences for the 0–5 cm layer ($p < .05$), with the lowest C stock found in bare soil (TR). In the 0–10 cm layer, the soil C stock was 18.4, 17.7, 17.5 and 16.6 Mg/ha in NR, MR, HR and TR, respectively. The initial soil C stock in this layer was 16.4 Mg/ha, so there was an increase ($p < .05$) in C stocks in all treatments except TR, with NR presenting the highest C stock after two seasons of straw addition, followed by MR and HR. Soil C stocks in deeper layers did not change due to straw management. The DOC retention within the 1–20 cm soil layer represented 11% of the C stock increase in NR (312 kg/ha of retained DOC to 2,700 kg/ha in increased C stock), which was not sufficient to cause detectable changes in deeper layers.

4 | DISCUSSION

4.1 | DOC release from soil and straw

The total DOC flux released at 1-cm depth in NR in the first sampling period was 350 kg/ha, whereas at 20-cm depth was 180 kg/ha. These values are in agreement with DOC fluxes in similar environments reported by Neff and Asner (2001), showing the reliability of the results. Leaving straw on the soil surface favours soil water storage and water drainage to deeper layers (Gmach et al., 2019), as well as microbial abundance and activity (Moraes et al., 2019), positively affecting straw decomposition processes and, consequently, release of C as DOC to the soil (Leinweber et al., 2008). In the present study, having greater amounts of straw on the surface (NR) favoured water percolation throughout the soil profile. It is likely associated with a greater soil structure due to C input, which results in larger water storage (Gmach et al., 2019), better aggregation, and lower soil compaction (Castioni

TABLE 2 Sugarcane straw decomposition under different removal rates from the soil surface after first and second straw addition

Straw removal	First year			Second year			
	Straw-C applied[f]	Straw-C remaining[b]	Straw-C lost[c]	Straw-C applied[c]	Total straw-C [d]	Total straw-C remaining[e]	Total straw-C lost[f]
	g/m²						
HR	126	41	85 (67%)	126	167	76	176 (70%)
MR	252	57	195 (77%)	252	309	118	386 (76%)
NR	504	85	419 (83%)	504	589	270	738 (73%)

Abbreviations: HR, high removal (3 Mg/ha left on soil surface); MR, medium removal (6 Mg/ha); NR, no removal (12 Mg/ha).

[a]and [a"] Straw-C added * Average C concentration in straw was 420 g/kg.

[b]Straw-C remaining at the first year.

[c]Straw-C lost by decomposition at the first year (a' – b).

[d]Total straw-C, considering the straw remaining at the first year and the second straw application (b + a").

[e]Total straw-C remaining, considering the two years.

[f]Total straw-C lost by decomposition at the two years (a' + a" – e)

et al., 2019). While high removal rate (HR) reduced water percolation, and bare soil (TR) had lower soil moisture content (i.e. high evaporation; data not shown) and lower water percolation through the soil profile than soil with straw on the surface (Table S2), as also found by Awe et al. (2015).

Soil DOC is produced by different sources, such as decomposing fresh litter, root exudation or stable SOM decomposition (Hagedorn et al., 2004; Kalbitz et al., 2000; Neff & Asner, 2001). However, the relative contribution of these different sources is unknown. I this study, DOC concentration at 1-cm depth in the bare soil confirmed SOM as a DOC source (Fröberg et al., 2003; Zsolnay, 1996). However, it is important to highlight that DOC was responsive to straw management (Figure 1, Table 1), corroborating previous findings (e.g. Van Gaelen et al., 2014; Gregorich et al., 2000; Leinweber et al., 2008; Sousa Junior et al., 2018). The rate of DOC release to soil was reduced when the input of fresh organic material was reduced (i.e. high straw removal rates), suggesting that most of the DOC produced was derived from straw (see net-DOC straw-derived, Table 1; Michalzik et al., 2003). Thus, the large amount in DOC production from straw retention supports the recommendation on keeping a superficial soil cover (Thayalakumaran et al., 2015).

In general, higher DOC concentrations were found in drainage water during annual dry periods, after rain events occurring after droughts, than in periods with frequent rainfall (Figure 1). This was probably the result of dissolution of degradation products and microbial necromass accumulated over the dry period (Kalbitz et al., 2000). Furthermore, low soil water content (in additional to lower percolate flux) and long-time contact (straw-soil) may lead to higher DOC concentrations (McDowell & Wood, 1984). In contrast, during more frequent rainfall periods, a larger volume of water percolates through the soil profile, diluting the DOC concentration in drainage water. Although the total DOC fluxes were higher in rainy periods, the larger volume of percolating water and fast water movement probably decreased DOC sorption and microbial processing, resulting in higher transfer of straw-derived DOC into deeper soil layers (Kaiser & Kalbitz, 2012).

4.2 | DOC translocation and retention within the soil profile

The DOC content in the soil profile is a result of continuous sorption combined with microbial process and desorption. Part of the DOC released from straw on the soil surface is transported to deeper layers through water percolation, as a stabilized C source for deep soil layers (Fröberg et al., 2007). But DOC from fresh plant residues is largely retained in surface layers (Fröberg et al., 2007). The reduction in DOC down the soil profile is mainly attributable to C adsorption to soil minerals, such as clays and Fe and Al oxides

TABLE 3 Soil carbon stocks (Mg/ha) at each layer of the 100-cm soil column of different sugarcane straw removal rates from the soil surface after 17 months and two straw addition

	Soil C stock (Mg/ha)			
Depth cm	Total removal	High removal	Medium removal	No removal
0–5	8.6 ± 0.03 b*	9.2 ± 0.42 ab	9.3 ± 0.39 ab	9.9 ± 0.48 a
5–10	8.0 ± 0.11ns	8.2 ± 0.24	8.3 ± 0.46	8.4 ± 0.04
10–20	14.7 ± 0.67ns	14.9 ± 0.68	15.6 ± 0.42	15.6 ± 0.59
20–30	12.2 ± 0.52ns	12.3 ± 0.97	12.5 ± 1.04	13.3 ± 0.69
30–40	10.3 ± 0.85ns	10.3 ± 0.62	10.3 ± 0.72	10.6 ± 0.72
40–50	9.5 ± 0.14ns	9.5 ± 0.14	9.2 ± 0.42	8.9 ± 0.84
50–60	8.7 ± 0.41ns	8.8 ± 0.26	8.9 ± 0.13	8.3 ± 0.40
60–70	8.5 ± 0.04ns	8.2 ± 0.37	8.3 ± 0.15	8.2 ± 0.17
70–80	8.2 ± 0.38ns	8.0 ± 0.25	7.9 ± 0.15	8.3 ± 0.33
80–90	8.2 ± 0.23ns	8.2 ± 0.39	8.3 ± 0.23	8.5 ± 0.53
90–100	8.1 ± 0.31ns	8.7 ± 0.85	8.2 ± 0.37	8.2 ± 0.38

*Mean values followed by the same letter within each soil depth did not differ according to Tukey's test ($p < .05$).

(Fujii et al., 2013; Kaiser & Guggenberger, 2000; Kaiser et al., 1996), common in this soil due to weathering processes. In only 15 min, 60%–90% of DOC percolating to the subsoil may be retained by sorption (Kaiser & Zech, 1998). Thus, the DOC fluxes are larger in the topsoil and decline with depth (Gregorich et al., 2000; Hassan et al., 2016), as also found in this study (Table 1).

The differences on DOC retention between soil layers can be also explained by the DOC composition. Studies about DOC composition were mainly conducted in aqueous systems, and only a few studies were aimed at investigating DOC composition in soil, especially under field conditions (Dong et al., 2019; Gmach et al., 2020). In some preliminary results, we found different specific ultraviolet absorbance (SUVA, l/g cm^{-1}) between treatments (Table S3), in which higher values suggesting presence of more recalcitrant materials while low values are associated with more labile materials. The SUVA value in NR at 1-cm depth tending to be high in the beginning but low at the end of both sampling periods, while that in TR was high throughout. At 20-cm depth, SUVA in TR again tended to be high, while NR showed low values. This suggests that TR had more recalcitrant material, likely originating from stable SOM, whereas in NR it was less recalcitrant, deriving from fresh organic material (Chin et al., 1994). Thus, the DOC produced from different straw amounts seemingly indicated changes in composition due to difference in sources coming from SOM.

Bare soil (TR) showed an increase in DOC flux at 20-cm depth, compared with the topsoil (Table 1), indicating C loss from the top SOM to deeper soil layers. The main DOC retention occurred within the first 50 cm of soil for all treatments and represented approximately 84% of total DOC in the treatments with straw, while between 50- and 100-cm depth, DOC retention was less than 2% of the total retained. Here, DOC leaching below 100-cm depth showed little difference between NR and TR (<12 kg/ha), as found by Janeau et al. (2014). Leaching of DOC below 100 cm was not proportionally to the straw rates, representing 13%–16% of total DOC released in the soils with straw, while it represented 30% in bare soil (TR). Lower C losses were found in soil tillage system keeping all the residues on the surface (Chowaniak et al., 2020). These results reaffirm that DOC derived from SOM differs in reactivity and sorption characteristics.

4.3 | Effects on soil carbon storage and soil functioning

Climate regulation through C sequestration in the soil is one of principal ecosystem service that people obtain from the soil (Adhikari & Hartemink, 2016). Moreover, soil C sequestration is associated with other key soil-related ecosystem services, such as food production, water regulation, erosion control, nutrient cycling and water purification (Lal, 2004; Wiesmeier et al., 2019). The DOC fraction is a potential source of stabilized C occurring in subsoil by C redistribution to deep layers (Froberg et al., 2007), leading to SOC accumulation and making an important way to sequester C and decrease C loss in the CO_2 form (Lal, 2004; Smith, 2004).

We observed changes on soil C stocks in this study in the upper soil layer (Table 3). The strong correlation between DOC release and straw-C losses indicates that larger decomposition rates caused greater DOC production. Since straw decomposition rate increases with increasing straw amount left on the soil (Varanda et al., 2019), straw removal translates directly into less DOC production. The highest soil C stock was found in NR, corroborating the finding of large DOC release and retention in the topsoil. Moreover, there was an increase in C stock from beginning to the end of the study period in the first 10-cm depth in the soils with straw addition (highest in NR, followed by MR and HR), while for TR the C stock remained unchanged. DOC retention was strong in the topsoil, contributing 11% of the C stock increase in NR (312 kg/ha of retained DOC to 2,700 kg/ha in increased C stock). On the other hand, based on the evidence of DOC translocation and leaching in TR, and no C input in the soil, it can be assumed that C stocks would decline even in deeper layers under longer-term indiscriminate straw removal.

Even in small amounts, DOC helps to sustain several ecosystem services in the soil. DOC is the main C source for utilization by soil microorganisms (Chantigny, 2003; Kalbitz et al., 2000). Soil microbial activity is positively related to DOC content (Li et al., 2019), and there is a specific link between DOC chemodiversity and bacteria community. Organic carbon inputs via crop residues build soil C and increase the resilience, besides mediate the functional state of soil bacterial communities. Significant alterations in the abundance of bacteria, archaea and fungi are associated with straw removal (Moraes et al., 2019) altering decomposition processes.

The increase in microbial activity and increase in SOC mobility can be determined by soil pH (Curtin et al., 2016; Tipping & Hurley, 1988), which is positively correlated with DOC content (Li et al., 2019). DOC mobilization can increase at high pH due to the reduced adsorption capacity of soils (Tipping & Woof, 1990). It is in agreement with our results, in which the soil has low pH and had high DOC adsorption. Our results support the thinking that DOC has an important role to C percolation to deeper soil, C retention and C storage, favouring microorganism activity and acting in very important process in the soil.

5 | CONCLUSIONS

Straw removal management negatively affects the concentration of DOC in the soil. These effects are more relevant for surface soil layers, where straw removal reduces DOC concentration and total soil C stock, even in the short term. Bare soil loses C from topsoil to deeper soil layers. The amount of straw little affects DOC leaching below 100-cm depth, suggesting that straw-derived DOC predominantly remains in this top 100 cm layer.

Our data showed that sugarcane straw removal might be a sustainable management, and however, at least 3 Mg/ha of straw should be kept on the soil surface to sustain DOC concentration and soil C stocks in these soil/climate conditions. In this study, dissolved organic C represents a small fraction (11%) of total soil C stock increase, but it is well known that DOC contributes to key soil functions (e.g. C storage and CO_2 mitigation, microbial activity and maintenance, nutrient cycling and retention, pesticide inactivation) and should be taken into account for more sustainable straw management in Brazil.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data available on request from the authors. The data support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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