Received: 22 March 2024 | Revised: 18 July 2024 | Accepted: 19 July 2024

DOI: 10.1111/gcbb.13188

Global Change Biology Bioenergy
BIOPRODUCTS FOR A SUSTAINABLE BIOECONOMY
WILEY

RESEARCH ARTICLE

Soil carbon stocks in sugarcane cultivation: An evidence synthesis associated with land use and management practices

Carlos Roberto Pinheiro Junior[1] | **João Luís Nunes Carvalho**[2] | **Lucas Pecci Canisares**[1] | **Carlos Eduardo Pellegrino Cerri**[1,3] | **Maurício Roberto Cherubin**[1,3]

[1]Department of Soil Science, "Luiz de Queiroz" College of Agriculture, University of São Paulo, Piracicaba, Brazil

[2]Brazilian Biorenewables National Laboratory / Brazilian Center for Research in Energy and Materials (LNBR/CNPEM), Campinas, Brazil

[3]Center for Carbon Research in Tropical Agriculture (CCARBON), University of São Paulo, Piracicaba, Brazil

Correspondence
Carlos Roberto Pinheiro Junior and Maurício Roberto Cherubin, Department of Soil Science, "Luiz de Queiroz" College of Agriculture, University of São Paulo, Piracicaba,São Paulo, Brazil.
Email: robertojrpinheiro@gmail.com and cherubin@usp.br

Funding information
Conselho Nacional de Desenvolvimento Científico e Tecnológico, Grant/Award Number: 311787/2021-5; Fundação de Amparo à Pesquisa do Estado de São Paulo, Grant/Award Number: 2023/08814-9, 2023/11337-8 and 21/10573-4

Abstract
Biofuels are essential to ensure the energy transition and mitigating of climate change. However, understanding the impact of land use change (LUC) and management practices on soil organic carbon (SOC) stocks is fundamental to ensuring well-founded policymaking and assessing the sector's carbon footprint. Here, we conducted a meta-analysis (511 pairwise observations) to obtain Brazil's SOC stock change factors (SOC_{scf}) for LUC and management practices in sugarcane fields. Our results showed that converting native vegetation to sugarcane reduced the SOC stock in all assessed periods. The conversion from annual crops to sugarcane showed a reduction in SOC stock in the first 10 years but with a recovery over time. The conversion of pasture to sugarcane reduced the SOC stock only in the 10–20-year period and had a neutral effect in other periods evaluated. However, our dataset showed high variability in SOC_{scf}, with many observations indicating an increase in SOC stock, which is related to degraded pastures. We observed that the SOC accumulation rate for each ton of sugarcane straw was affected by the interaction between soil texture and precipitation. Regarding straw management, a low removal rate (< 34%) did not affect the SOC stock, while moderate (34%–66%) and high (> 66%) removal resulted in losses of 5.0% (SOC_{scf} 0.950) and 9.9% (SOC_{scf} 0.901), respectively. Our results also showed that reduced tillage and vinasse application increased SOC stocks by 24.0% (SOC_{scf} 1.24) and 10.0% (SOC_{scf} 1.10) respectively, proving to be good strategies to support C sequestration in sugarcane fields. Finally, we highlight that our results can contribute to the improvement of public policies and also be used in future life cycle assessment (LCA) and modeling studies, as they provide robust data to establishing regional SOC_{scf} induced by LUC and management practices, enhancing the reliability of the C footprint assessment of biofuel production.

KEYWORDS
climate change mitigation, LUC factor, organic amendment, RenovaBio, SOC changes, straw management

1 | INTRODUCTION

Accelerating the energy transition from fossil fuels to sustainable energy sources (i.e., bioenergy) has been widely recognized as an important pathway to achieving the net-zero greenhouse gases (GHG) emissions and ensuring global energy security (García-Freites et al., 2021; Van Soest et al., 2021). Given this scenario, Brazil stands out globally as the largest sugarcane producer, accounting for 40% of world production (FAOSTAT, 2022) and as the world's second-largest producer of bioethanol (IEA, 2023), with more than 27 billion liters of sugarcane ethanol (CONAB, 2023). Furthermore, Brazil is a pioneer in elaborating public policies in the ethanol sector and one of the leaders of the Global Biofuel Alliance (IEA, 2023), recently launched at the G20 meeting in September 2023.

To encourage the adoption of sustainable practices by the sector, the National Biofuels Policy (RenovaBio) enables the negotiation of Decarbonization Credits (CBIOs) by duly accredited producers of low-emission biofuels (Brazil, 2017). In 2023, CBIOs negotiations represented R$3.4 billion reais (~ $680 million dollars), with growth projections for the coming years (Brazil, 2023). However, although land use change (LUC) and management practices are the main drivers of changes in soil organic carbon (SOC) stocks (Lal, 2021; Ramesh et al., 2019; Sanderman et al., 2017), they are not yet accounted for by the tool used to calculate ethanol GHG emissions and CBIOs generation (called RenovaCalc). In a recent study, Bordonal et al. (2024) found that the inclusion of SOC changes induced by land use and management changes significantly modifies the life cycle GHG emissions of sugarcane-based bioenergy. It is important to emphasize that SOC changes due to land use and management changes can be accounted for using default factors provided by the International Panel of Climate Change (IPCC) or by regional (Tier 2) factors derived from local measurements.

In Brazil, in the last decades, several studies have shown the effect of different LUC scenarios (e.g., Bordonal et al., 2017; Franco et al., 2015; Mello et al., 2014) and sugarcane management practices (e.g., soil tillage, harvesting system, straw removal) on SOC stocks (Galdos et al., 2009; Popin et al., 2020; Tenelli et al., 2019). Considering land use changes, studies have shown that the expansion of sugarcane cultivation in Brazil has occurred predominantly from pasture areas (Adami et al., 2012; Cherubin, Bordonal, et al., 2021; Oliveira et al., 2019) and the effect of this transition on SOC stocks was varied (Franco et al., 2015; Mello et al., 2014; Oliveira et al., 2016; Silva-Olaya et al., 2017). These studies highlight the level of pasture productivity before conversion as the main driver for SOC changes, however, the vast majority of them are local studies, which makes a more robust assessment difficult. Furthermore, the wide range of edaphoclimatic conditions in sugarcane cultivation areas in Brazil affects SOC dynamics and, consequently, sensitivity to different management practices.

Regarding the effects of management strategies on SOC changes several practices were evaluated. Overall, it was that sugarcane straw represents the main C input into the soil (Carvalho et al., 2017), thus high rates of straw removal—used to produce second-generation (2G) ethanol or bioelectricity—reduce the SOC stock, which has different sensitivity depending mainly on soil texture (Popin et al., 2020; Satiro et al., 2017; Tenelli et al., 2021). Other studies have shown that no-tillage (Silva-Olaya et al., 2013; Tenelli et al., 2019), cover crops (Carneiro et al., 2024), and recycling of sugarcane industry residues (Zani et al., 2018) can make important contributions to SOC sequestration.

While numerous local studies have investigated the effects of land use and management changes on SOC stocks, there is a lack of comprehensive studies that have systematized the local literature and derived regional factors. Therefore, there is an urgent need to develop specific factors (Tier 2) for SOC changes that better represent the prevailing edaphoclimatic conditions of the areas under sugarcane production in Brazil. Establishing regional SOC stock factors induced by land use and management changes represents a step forward in refining the real impacts/benefits of sugarcane bioenergy production in Brazil. Therefore, this study aimed to compile the scientific literature through a meta-analysis to establish the SOC stock change factors for sugarcane cultivation in Brazil. We believe that the compilation of these data can provide robust results that contribute to the improvement of public policies and can be used in life cycle assessment (LCA) and modeling studies, allowing a more reliable assessment of the C footprint of ethanol produced from sugarcane.

2 | MATERIALS AND METHODS

2.1 | Data collection

To assess the land use and sugarcane management changes on SOC stock, we conducted a meta-analysis with the data available in the literature. The data were extracted from the Scopus and Web of Science databases. The terms used in the search were ((“soil organic carbon” OR “soil organic matter” OR “soil carbon”) AND (“sugarcane” OR “sugar cane”) AND (“Brazil*”)). The *revtools* package (Westgate, 2019) in the R software was used to eliminate repetitions between the papers found in the databases, obtaining a total of 2366 scientific papers (Figure S1). For a first selection (first filter), we considered all articles containing the term “stock” and obtained 465 scientific papers. In the second selection stage, we considered only studies that evaluated the effect of LUC and sugarcane management practices (i.e., soil tillage, straw removal, and vinasse application) on SOC stock changes, resulting in 20 scientific papers published between 2007 and 2023 (Table S1). These papers covered 60 study sites, predominantly located in central southern Brazil (Figure 1), the largest sugarcane-producing region of the world.

2.2 | Data processing and statistical analysis

The compiled dataset contained 511 pairwise observations containing SOC stock of sugarcane fields against the previous land use (land use change effect) or the management effect (straw removal, vinasse application, or tillage).

2.2.1 | Land use and management effects on SOC stock

The dataset included studies in which soil samples were taken from sugarcane fields with the previous land uses of pasture, annual crops, or native vegetation, with SOC stock calculated for the following layers: 0–10 cm, 0–30 cm, 0–50 cm, or 0–100 cm layers. This study also identified three management practices that could impact the SOC stock of sugarcane fields with the appropriate control treatments: straw removal, vinasse application, and soil tillage. We divided straw removal into three levels: low removal (<34%), moderate removal (34%–66%) and high removal (>66%). The land use and management effects were grouped according to previous land uses and individual management and the effect size was calculated as described in the following equations (Hedges et al., 1999):

$$\text{Response ratio (RR)} = \frac{\text{SOCt}}{\text{SOCc}} \tag{1}$$

$$\text{Effect size (ES)} = \ln(\text{RR}) \tag{2}$$

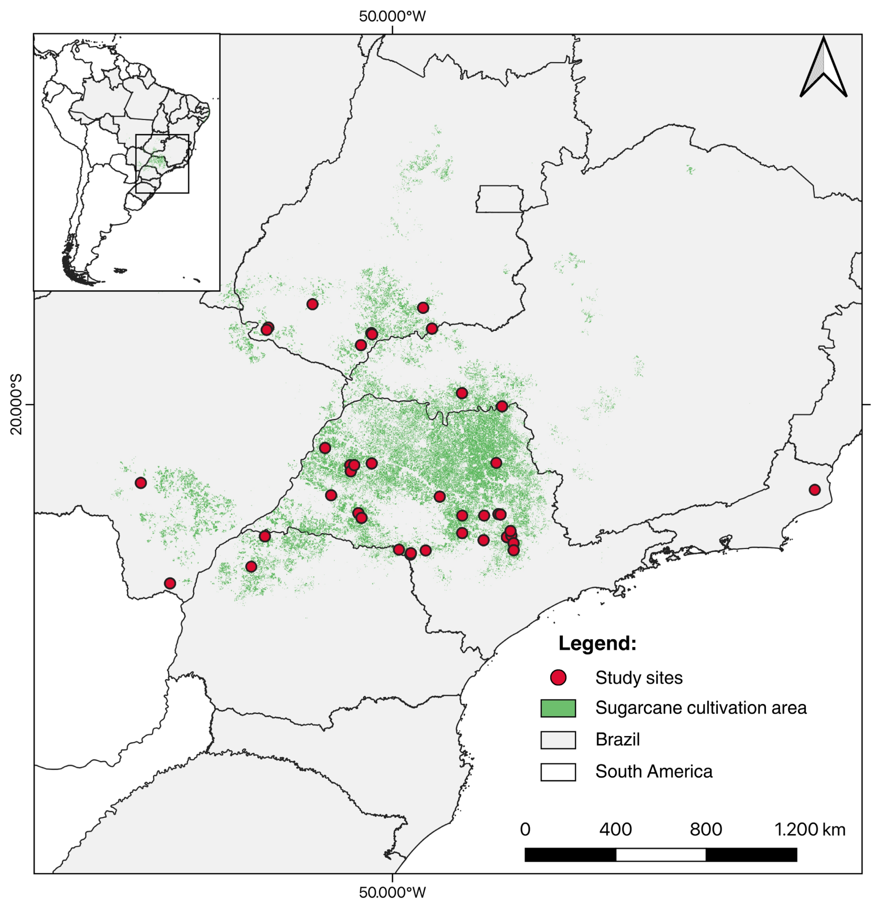

FIGURE 1 Geographical distribution of the study sites across the sugarcane production regions in Brazil.

where the SOC_t is the SOC stock of fields with the treatment effect (land use or management application) and SOC_c (land use of reference or without the management application) is the stock of paired observations without management (Mg ha^{-1}). Since multiple studies did not report the standard deviation or standard error, we estimated the sampling variance for weighing the effect size, using the following equation (Gurevitch & Hedges, 2001):

$$\text{Effect size variance} = \frac{N*N}{N+N} \quad (3)$$

The mean RR ranged between 1.01 and 0.99, indicating no bias in the soil layer evaluation (Figure S2). We used the *boot* function with 5000 permutations to calculate the confidence interval of 95%. Since the standard deviation or error was not reported in many studies, we used the *boot* function with 5000 permutations to calculate the confidence interval of 95%. The bootstrap results were used to calculate the average effect of land use change and management practices expressed in the SOC stock change factor (SOC_{scf}),

$$\text{SOC stock change factor (SOCscf)} = \exp^{\overline{ES}} \quad (4)$$

The original effect size, the bias, and the standard error of each bootstrap are reported in Table S2. All the statistical steps and data processing were done using *dplyr* package (Wickham et al., 2019) and R Core Team (2023).

2.2.2 | SOC accumulation rates in sugarcane fields

Our dataset included studies of straw removal, and we calculated the rates of SOC accumulation based on the length of time and mass of straw left in the field,

$$\text{SOC accumulation rates} = (\text{SOCS} - \text{SOCNS}) \div (\text{SM} * \text{Time}) \quad (5)$$

where the SOCS is the SOC stock of fields with straw and SOCNS is the stock of paired observations without straw (Mg ha^{-1}), SM is the straw mass (Mg ha^{-1} year^{-1}), and Time (experimental period) is used to convert for annual rates. The studies using straw removal treatments were not homogenized in soil layers; thus, we restricted our analysis of all SOC measurements of the topsoil (10 cm) since it was the common layer found in most of the studies. A linear mixed model was used to analyze the SOC accumulation rates calculated from the literature. The soil texture (sandy, loamy, and clayey) and the historical average cumulative precipitation (lower or higher than 1330 mm year^{-1}, the median of all sites) were used as fixed effects. The longitude was used as a random effect in the *lmer* function of *lmerTest* package to fit a Gaussian error distribution on the dataset (Kuznetsova et al., 2017).

3 | RESULTS

3.1 | Effect of land-use changes on SOC stocks

Our dataset showed that the majority of studies evaluated the conversion of pasture to sugarcane (n = 188), but to a lesser extent, studies also evaluated the conversion of annual crops (n = 39) and native vegetation (n = 15) to sugarcane. The conversion of pasture to sugarcane areas showed a neutral effect for SOC stock changes for both the 0–10 years and >20 years (SOC_{scf} of 0.997 for both) while for the 10–20 years period, the SOC_{scf} was 0.989, indicating a 1.1% reduction (Figure 2a). However, our dataset also showed a considerable number of observations with SOC_{scf} higher than 1.0, indicating an increase in SOC stock for this conversion (Figure 2b).

For 0–10 years, the conversion of annual crops to sugarcane showed a SOC_{scf} of 0.984, indicating a 1.6% reduction. Considering the period of 10–20 years, the effect on the SOC stock change was neutral, while for the areas under sugarcane for more than 20 years an increase of 1.0% increase was observed (SOC_{scf} 1.01), which indicated a recovery of SOC stocks over time. For the conversion of native vegetation to sugarcane, the SOC_{scf} were 0.967 (−3.3%), 0.991 (−0.9%), and 0.992 (−0.8%) for the periods of 0–10 years, 10–20 years, and >20 years, respectively, indicating a reduction in SOC stocks in all evaluated periods.

3.2 | Effect of sugarcane management practices on SOC stocks

3.2.1 | SOC accumulation rates and straw removal

We observed that the average SOC accumulation rate for each ton of sugarcane straw was 45.4 kg ha^{-1} year^{-1} Mg of straw^{-1}. However, this rate was affected by the interaction between soil texture and precipitation (Table S3). We observed that sandy soils have the potential to accumulate 4.3 times more SOC in the topsoil when it is in sites with annual precipitation higher than 1330 mm (79.4 kg ha^{-1} year^{-1} Mg of straw^{-1}) in comparison with sites with lower precipitation (18.4 kg ha^{-1} year^{-1} Mg of straw^{-1}). For loamy soils, the SOC accumulation rate was 37.4 and 57.8 kg ha^{-1} year^{-1} Mg of straw^{-1} at sites with annual precipitation levels above and below 1300 mm,

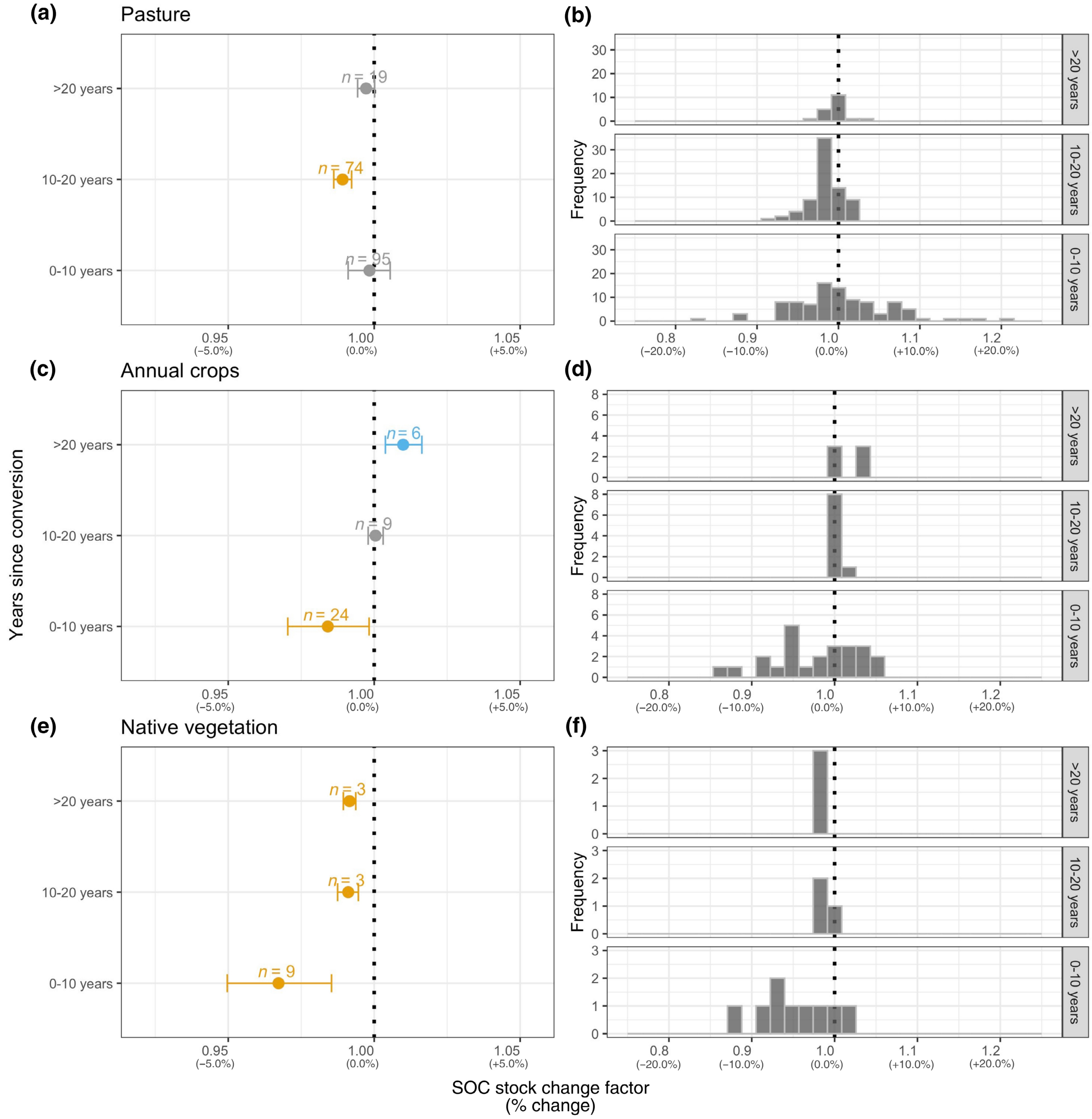

FIGURE 2 SOC stock change factor and data distribution (histogram) for conversion from pasture (a, b), annual crops (c, d), and native vegetation (e, f) to sugarcane. The colors orange, gray, and blue indicate a scenario of loss, neutrality, and gain of SOC stock, respectively.

respectively. Whereas for clayey soils, the SOC accumulation rate was 40.1 and 39.3 kg ha^{-1} $year^{-1}$ Mg of $straw^{-1}$ for the sites with precipitation above and below 1300 mm, respectively (Figure 3).

To assess the effect of sugarcane straw management, we calculated the SOC stock changes for three levels of straw removal (<34%, 34%–66%, and >66%) as compared to no straw removal scenario (Figure 4). The low removal (<34% of straw removal), showed no difference in the SOC stocks when compared to no removal. For removal levels of 34%–66% (moderate removal) and >66% (high removal), the SOC_{scf} were 0.950 (−5.0%) and 0.901 (−9.9%), indicating significant SOC losses. It is important to highlight that the SOC stock measurements were taken in experiments ranging from 11 to 48 months, with a median duration of 24 months. Thus, this RR represents a short-term evaluation period.

3.2.2 | Organic amendments—vinasse application

The application of vinasse had a positive effect on SOC stocks, resulting in a 10.0% increase (SOC_{scf} 1.10) for the soil layers that showed a statistical difference (Table 1). Although filter cake is a very common organic amendment

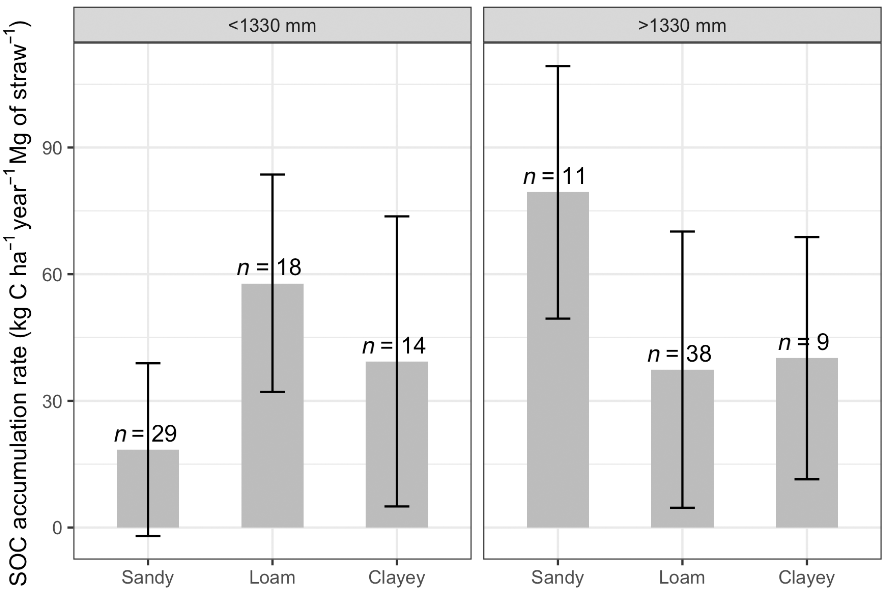

FIGURE 3 Average SOC accumulation rates of sugarcane straw in the top 10 cm soil layers as affected by the level of precipitation and soil texture. The error bars represent the confidence intervals for 95%. Prec.: Historical average annual precipitation for the last 30 years.

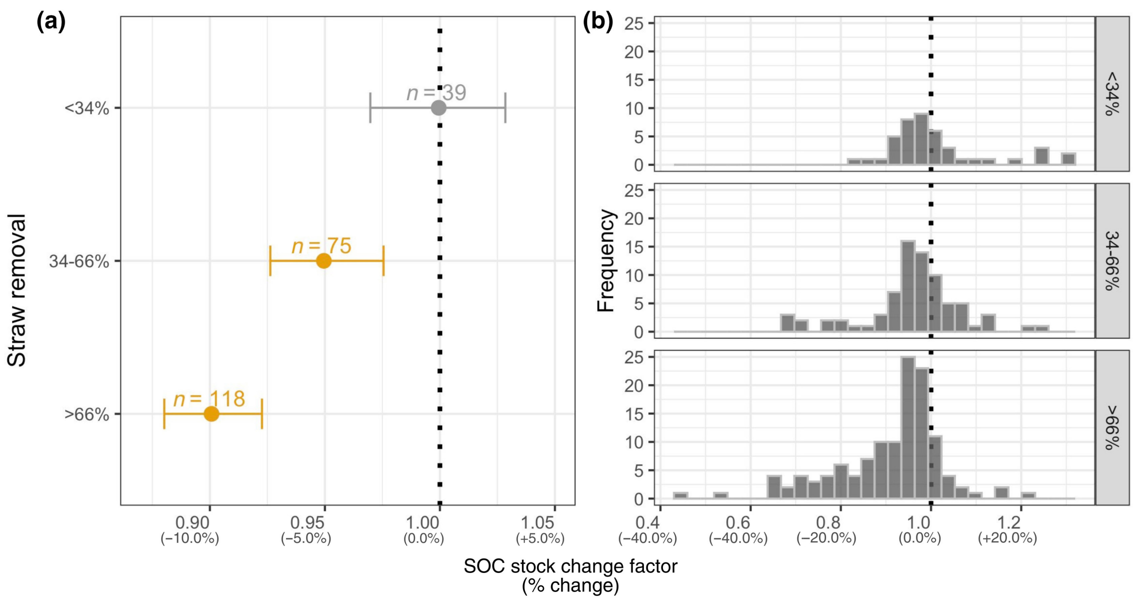

FIGURE 4 SOC stock change factor (a) and data distribution (b; histogram) by three levels of straw removal (<34%, 34%–66%, and >66%) in sugarcane cultivation in Brazil. The circles represent the average response ratio of each straw removal level, and the bars represent the 95% confidence interval obtained by bootstrapping with 5000 interactions. The gray and yellow colors represent the removal rates that have neutral and negative response ratios, respectively.

in sugarcane production, we found no papers with the control treatment that allow us to evaluate the effect of its application on SOC stocks.

3.2.3 | Soil tillage

We identified three papers that evaluated different soil tillage practices, comparing conventional tillage with reduced tillage or deep tillage (Table 2). However, only the study by Segnini et al. (2013) observed a statistical difference with the adoption of reduced tillage, with SOC_{scf} of 1.24, indicating a 24.0% increase in SOC stocks in the 0–5 cm layer.

4 | DISCUSSION

4.1 | Land-use change scenarios

Our study synthetized that existing information and provided robust results on the effect of converting different land uses to sugarcane cultivation on SOC stock change factors and their variation over time. Converting native

TABLE 1 Effect of vinasse application on SOC stock change factor (SOC_{scf}) of sugarcane fields.

Study	Treatment	Soil layer	SOC_{scf}	Statistical differences
Canellas et al. (2007)	Vinasse vs. no vinasse	0–20	1.08	Significant
		20–40	1.04	ns
Cardin et al. (2016)	Vinasse vs. no vinasse	0–10	1.11	ns
		10–20	1.10	ns
		20–30	0.96	ns
		30–40	0.93	ns
		40–50	1.00	ns
Zani et al. (2018)	Vinasse vs. no vinasse	0–30	1.10	Significant*
		0–50	1.13	Significant*
		0–100	1.09	Significant*

Abbreviation: ns, no significant.
*$p < 0.05$.

TABLE 2 Effect of different soil tillage practices on SOC stock change factor (SOC_{scf}) of sugarcane fields.

Study	Site	Treatment	Soil layer	SOC_{scf}	Statistical differences
Tenelli et al. (2019)	1	Reduced tillage vs. conventional	0–10	1.17	ns
			0–40	1.12	ns
	2		0–10	1.03	ns
			0–40	1.09	ns
Scarpare et al. (2019)	1	Deep tillage vs. conventional	0–10	0.86	ns
			10–20	0.85	ns
			20–40	1.09	ns
			40–60	1.04	ns
			60–80	0.94	ns
			80–100	0.88	ns
Segnini et al. (2013)	1	Reduced tillage vs. conventional	0–5	**1.24**	Significant*
			5–10	1.14	ns
			10–20	0.92	ns
			20–60	1.06	ns

Abbreviation: ns, no significant.
*$p < 0.05$.

vegetation to sugarcane resulted in SOC stock losses in all the periods evaluated, with SOC_{scf} of 0.967, 0.991, and 0.992 in 0–10 years, 10–20 years, and >20 years, respectively. Furthermore, converting native vegetation areas to sugarcane also results in a large loss of biomass C stock, increasing C debt and payback time (Alkimim & Clarke, 2018). However, considering the offset of 9.8 Mg CO_2 ha^{-1} $year^{-1}$ by ethanol production (Fargione et al., 2008), the carbon payback time for converting native vegetation to sugarcane in the Cerrado biome obtained by Mello et al. (2014) was 8 years, while Alkimim and Clarke (2018) found payback times of 15, 22 and 62 years for the Cerrado, Atlantic Forest and Amazon biomes, respectively. Despite the higher C debt, the conversion of native vegetation to sugarcane in the period 2000–2009 was less than 1% in south-central Brazil (Adami et al., 2012), a region that accounts for more than 90% of national sugarcane production (CONAB, 2023). However, it is important to highlight that the Brazilian Biofuel Policy (RenovaBio) does not encourage the expansion of sugarcane in native vegetation areas, and biofuels produced in these areas are eligible for certification and payment of decarbonization certificates (CBIOs).

However, it is important to highlight that our regional SOC_{scf} for conversion from native vegetation to sugarcane indicates a lower impact on SOC stock reduction when compared to the value of LUC factors for conversion from native vegetation to cropland established by the IPCC defaults (Tier 1; IPCC, 2019). Sugarcane is a semi-perennial crop and although soil tillage reduces SOC stock, it only occurs every 6 years in the replanting time. Thus, the LUC factor of 0.83 for the wet tropical climate, which considers the baseline condition of annual full soil tillage, would result in an overestimation of SOC stock losses in sugarcane fields. However, in our dataset, few observations were made for over 20 years of land use conversion, which limits a more robust conclusion.

Our results showed that conversion from pasture to sugarcane reduced the SOC stocks only in the 10–20 year period and showed a neutral effect for the other time spans evaluated. Our results also showed a wide variation in SOC_{scf} to this land use conversion, and a large number of observations indicated an increase in SOC stock (Figure 2b). This variability in the SOC_{scf} by pasture conversion may be mainly related to pasture degradation level (Cherubin, Bordonal, et al., 2021). Indeed, the expansion of sugarcane cultivation over extensive and degraded pasture areas increases SOC stock (Franco et al., 2015; Oliveira et al., 2016; Schiebelbein et al., 2023). Thus, converting these areas with low SOC stock to sugarcane represents an opportunity to increase SOC sequestration, contributing to climate change mitigation and other ecosystem services (Cherubin et al., 2021; Oliveira et al., 2019).

A study conducted by Hernandes et al. (2021) showed that there are 20 million hectares of pastures in central southern Brazil with suitable conditions for expanding sugarcane production. In the Cerrado biome alone, there are more than 3 million hectares of degraded pastures (Alkimim & Clarke, 2018) where the expansion of sugarcane cultivation represents an opportunity to mitigate climate change through SOC sequestration and ethanol production. In addition, the study conducted by Oliveira et al. (2019) showed that the conversion of degraded pastures to sugarcane cultivation for ethanol production can improve different sustainability indices and the provision of ecosystem services, as well as contribute to climate change mitigation.

The conversion of annual crops to sugarcane, although resulting in a negative initial impact, shows a recovery in the period of 10–20 years, and an increase in SOC stock after 20 years. Although converting annual crops to sugarcane shows a positive impact on SOC sequestration over time, it can raise the debate about the direct competition between food and biofuel production. In addition, the profitability of annual crops is higher than sugarcane, making this type of conversion unlikely in the current market scenario. Thus, it is more reasonable to project the expansion of sugarcane cultivation under degraded pastures, with greater economic and environmental benefits, due to the large area of pastures in Brazil having some degree of degradation (Lapig, 2024).

4.2 | Management practices

We investigated the SOC accumulation rates of sugarcane straw in different environments (soil texture and site precipitation) as well as the management effects (straw removal, organic amendments, and tillage) on SOC stock changes. Our results showed a high variability in the SOC accumulation rates for sandy soils as a function of average annual rainfall. This result may be associated with the greater sensitivity of sandy soils to management practices, affecting the physical, chemical, and biological attributes of the soil more significantly than clayey soils (Castioni et al., 2019; Cherubin, Carvalho, et al., 2021; Menandro et al., 2019). Sandy areas with an annual rainfall of less than 1330 mm, the SOC accumulation rate was only 18 kg Mg of straw^{-1} (1.8%), which would theoretically justify greater straw removal for bioenergy production. Nevertheless, high straw removal rates in sandy soils result in a drastic reduction in soil water availability—as the straw acts as a barrier to preserve soil moisture—as well as an increase in soil temperature and a loss of stalk yield (Carvalho et al., 2019; Castioni et al., 2019; Santos et al., 2021), especially under drier conditions (precipitation <1330 mm). Thus, under these conditions, high straw removal rates would result in high sugarcane yield losses and, consequently, a lower supply of straw in subsequent years, making this practice economically less competitive.

Our results showed that a low straw removal level did not affect the SOC stock, while moderate and high removal rates resulted in a 5.0% (SOC_{scf} 0.950) and 9.9% (SOC_{scf} 0.901) reduction in the SOC stock, respectively. These results, especially for high removal (i.e., low residue return to the soil surface), were similar to those set by the IPCC defaults (0.92; IPCC, 2019) for wet tropical climates. Given the economic interest due to the potential for bioenergy production (2G-ethanol and electricity) from sugarcane straw in a high removal level scenario, SOC stock losses should be compensated through a set of good management practices. Few studies have assessed the effect of different soil tillage methods on SOC stock changes in sugarcane areas, which limits a more robust assessment of this management practice. However, our results showed that the SOC stock was 24.0% higher (SOC_{scf} 1.24) under reduced tillage when compared to conventional tillage, while the IPCC default establishes a management factor of only 1.04 for adopting reduced tillage (IPCC, 2019). It is important to note that the IPCC value was obtained mainly for annual crops, which do not represent a sugarcane production system. In sugarcane cultivation areas, the intense mechanization increases soil physical degradation, especially due to soil compaction, and therefore conventional tillage is the business-as-usual scenario in the replanting time, which occur in each (five or six-years period). Thus, soil compaction has been one of the main challenges for the adoption of more conservationist tillage systems that reduce SOC losses (i.e., reduced tillage). Nevertheless, a recent study conducted by Luz et al. (2023) showed that reduced tillage associated with machinery traffic control are suitable management strategy to prevent physical degradation over sugarcane cultivation.

In Brazil, the most common way of harvesting straw is by raking, baling, and transporting the residue left on the soil surface after harvesting the sugarcane stalks. Nevertheless, this set of mechanized operations results in additional soil compaction and consequently reduces soil physical quality (Castioni et al., 2021). Conversely, the adoption of the integral harvesting system where the sugarcane stalk and straw are harvested and transported together, not only has a lower effective cost (Cardoso et al., 2013; Lisboa et al., 2017) but also reduces the number of mechanized operations in the field, reducing the risk of soil compaction. Thus, machine traffic control combined with the integral straw harvesting system could contribute to improving soil physical quality, allowing the adoption of the reduced tillage system in sugarcane areas and reducing SOC losses.

Our results showed that the vinasse application (organic residue from ethanol production) in sugarcane areas increases by 10.0% SOC stock (SOC_{scf} 1.10). The C content of vinasse is low (12.4 g kg^{-1}; Table S4), however, depending on its application rate, the annual C input can reach 800 kg C ha^{-1}. Furthermore, vinasse application increases nutrient cycling and soil moisture, contributing to higher sugarcane yields and increased straw production and C input into the soil (Cherubin et al., 2021; Rossetto et al., 2018).

5 | SUMMARY AND FINAL REMARKS

Our study provides an overview on the effect of land use change and sugarcane management practices on SOC stock changes in Brazil. The conversion of native vegetation to sugarcane resulted in SOC stock losses, regardless of the period considered. Although the conversion from annual crops to sugarcane shows an initial loss, the SOC stock has recovered over time. However, expansion of sugarcane cultivation in annual crop areas may generate land use competition with other food crops. Thus, expanding sugarcane cultivation over degraded pastures is suggested as the most feasible scenario, since it contributes to increasing SOC stocks and bioenergy production.

Overall, the low straw removal level has no significant effect on SOC stock, while moderate and high removal rates resulted in reductions of 5.0% and 9.9%, respectively. On the other hand, adopting reduced tillage can increase SOC stock by up to 24.0% (SOC_{scf} 1.24), proving to be an alternative to support SOC sequestration. Although vinasse application as an organic amendment is a low C input, it favors crop development and straw production, increasing SOC stock by 10.0% (SOC_{scf} 1.10). Few studies have reported the effect of different soil tillage methods and vinasse application on C stocks, thus further studies are necessary for a robust assessment. Our study was a review of all available information on the impact of land use and management changes on SOC stocks in sugarcane areas in Brazil. Nevertheless, we highlight the need for standardized methodological protocols (e.g., the thickness of soil layers collected) and treatments with appropriate controls for practices commonly adopted in sugarcane fields (e.g., filter cake application).

The trade-offs of using sugarcane crop residues for bioenergy production must be carefully thought. It is important to emphasize that the effects of straw removal and other management practices are not limited to changes in SOC stocks and that multiple ecosystem services need to be considered by decision-makers. Finally, we highlight that our results can contribute to the improvement of public policies and also be used in future modeling studies in order to enhance the reliability of the C footprint of sugarcane-based products.

AUTHOR CONTRIBUTIONS

Carlos Roberto Pinheiro Junior: Conceptualization; formal analysis; investigation; methodology; visualization; writing – original draft; writing – review and editing. **João Luís Nunes Carvalho:** Conceptualization; writing – original draft; writing – review and editing. **Lucas Pecci Canisares:** Conceptualization; data curation; formal analysis; methodology; software; validation; writing – original draft; writing – review and editing. **Carlos Eduardo Pellegrino Cerri:** Conceptualization; writing – original draft; writing – review and editing. **Maurício Roberto Cherubin:** Conceptualization; project administration; resources; supervision; writing – original draft; writing – review and editing.

ACKNOWLEDGMENTS

We thank the support from the Center for Carbon Research in Tropical Agriculture (CCARBON) at the University of São Paulo, sponsored by the São Paulo Research Foundation (FAPESP) under grant 21/10573-4. We also thank the support of Raízen for developing this study. C.R.P.J. and L. P. C were funded by FAPESP [grant number 2023/11337-8; 2023/08814-9]. M.R.C. thanks the CNPq for his Research Productivity Fellowship (311787/2021-5).

CONFLICT OF INTEREST STATEMENT

The authors declare no competing interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.13118821.

ORCID

Carlos Roberto Pinheiro Junior https://orcid.org/0000-0002-2721-6704
João Luís Nunes Carvalho https://orcid.org/0000-0001-5089-9411
Lucas Pecci Canisares https://orcid.org/0000-0002-7356-2894
Carlos Eduardo Pellegrino Cerri https://orcid.org/0000-0002-4374-4056
Maurício Roberto Cherubin https://orcid.org/0000-0001-7920-8362

REFERENCES

Adami, M., Rudorff, B. F. T., Freitas, R. M., Aguiar, D. A., Sugawara, L. M., & Mello, M. P. (2012). Remote sensing time series to evaluate direct land use change of recent expanded sugarcane crop in Brazil. *Sustainability*, *4*(4), 574–585. https://doi.org/10.3390/su4040574

Alkimim, A., & Clarke, K. C. (2018). Land use change and the carbon debt for sugarcane ethanol production in Brazil. *Land Use Policy*, *72*, 65–73. https://doi.org/10.1016/j.landusepol.2017.12.039

Bordonal, R. O., Lal, R., Ronquim, C. C., de Figueiredo, E. B., Carvalho, J. L. N., Maldonado, W., Jr., Milori, D. M. B. P., & La Scala Jr, N. (2017). Changes in quantity and quality of soil carbon due to the land-use conversion to sugarcane (*Saccharum officinarum*) plantation in southern Brazil. *Agriculture, Ecosystems & Environment*, *240*, 54–65. https://doi.org/10.1016/j.agee.2017.02.016

Bordonal, R. O., Tenelli, S., da Silva Oliveira, D. M., Chagas, M. F., Cherubin, M. R., Weiler, D. A., Campbell, E., Gonzaga, L. C., Barbosa, L. C., Cerri, C. E. P., & Carvalho, J. L. N. (2024). Carbon savings from sugarcane-straw derived bioenergy: Insights from a life cycle perspective including soil carbon changes. *Science of the Total Environment*, 947, 174670. https://doi.org/10.1016/j.scitotenv.2024.174670

Brazil. (2017). Lei No. 13576, de 26 de Dezembro de 2017— Dispõe Sobre a Política Nacional de Biocombustíveis (RenovaBio) e dá Outras Providências. https://www.planalto.gov.br/ccivil_03/_ato2015-2018/2017/lei/l13576.htm

Brazil—Ministério de Minas e Energia—Balanço RenovaBio. 2023. https://www.gov.br/mme/pt-br/assuntos/secretarias/petroleo-gas-naturalebiocombustíveis/renovabio-1/balanco-renovabio

Canellas, L. P., Baldotto, M. A., Busato, J. G., Marciano, C. R., Menezes, S. C., Silva, N. M., Rumjanek, V. M., Velloso, A. C. X., Simões, M. L., & Martin-Neto, L. (2007). Estoque e qualidade da matéria orgânica de um solo cultivado com cana-de-açúcar por longo tempo. *Revista Brasileira de Ciência Do Solo*, *31*(2), 331–340. https://doi.org/10.1590/s0100-06832007000200015

Cardin, C. A., Santos, C. H., & Escarmínio, M. A. (2016). Impacts of vinasse and methods of sugarcane harvesting on the availability of K and carbon stock of an Argisol. *Revista Ceres*, *63*(1), 95–102. https://doi.org/10.1590/0034-737x201663010013

Cardoso, T. D. F., Cavalett, O., Chagas, M. F., Morais, E. R. D., Carvalho, J. L. N., Franco, H. C. J., Galdos, M. V., Scarpare, F. V., Braunbeck, O. A., Cortez, L. A. B., & Bonomi, A. (2013). Technical and economic assessment of trash recovery in the sugarcane bioenergy production system. *Scientia Agricola*, *70*, 353–360. https://doi.org/10.1590/S0103-90162013000500010

Carneiro, M. P., de Souza, Z. M., Farhate, C. V. V., Cherubin, M. R., & Panosso, A. R. (2024). Effect of cover crops and tillage systems on soil quality and sugarcane yield. *Soil Use and Management*, *40*(2), e13048. https://doi.org/10.1111/sum.13048

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

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

Castioni, G. A., de Lima, R. P., Cherubin, M. R., Bordonal, R. O., Rolim, M. M., & Carvalho, J. L. (2021). Machinery traffic in sugarcane straw removal operation: Stress transmitted and soil compaction. *Soil and Tillage Research*, *213*, 105122. https://doi.org/10.1016/j.still.2021.105122

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

Cherubin, M. R., Bordonal, R. O., Castioni, G. A., Guimaraes, E. M., Lisboa, I. P., Moraes, L. A., Menandro, L. M. S., Tenelli, S., Cerri, C. E. P., Karlen, D. L., & Carvalho, J. L. (2021). Soil health response to sugarcane straw removal in Brazil. *Industrial Crops and Products*, *163*, 113315. https://doi.org/10.1016/j.indcrop.2021.113315

Cherubin, M. R., Carvalho, J. L. N., Cerri, C. E. P., Nogueira, L. A. H., Souza, G. M., & Cantarella, H. (2021). Land use and management effects on sustainable sugarcane-derived bioenergy. *Landscape*, *10*(1), 72. https://doi.org/10.3390/land10010072

CONAB—Companhia Nacional de Abastecimento. (2023). Acompanhamento de Safra Brasileira de Cana-de-açúcar. Volume 11—Safra 2023/2024, no. 1—Primeiro Levantamento—Abril 2023. https://www.conab.gov.br/info-agro/safras/cana/boletim-da-safrade-cana-de-acucar

FAO—Food and Agriculture Organization of the United Nations. (2022). *FAOStat*, *Land Use Data*. http://www.fao.org/faostat/en/#data/RL

Fargione, J., Hill, J., Tilman, D., Polasky, S., & Hawthorne, P. (2008). Land clearing and the biofuel carbon debt. *Science*, *319*(5867), 1235–1238. https://doi.org/10.1126/science.1152747

Franco, A. L., Cherubin, M. R., Pavinato, P. S., Cerri, C. E., Six, J., Davies, C. A., & Cerri, C. C. (2015). Soil carbon, nitrogen and phosphorus changes under sugarcane expansion in Brazil. *Science of the Total Environment*, *515*, 30–38. https://doi.org/10.1016/j.scitotenv.2015.02.025

Galdos, M. V., Cerri, C. C., & Cerri, C. E. P. (2009). Soil carbon stocks under burned and unburned sugarcane in Brazil. *Geoderma*, *153*(3–4), 347–352. https://doi.org/10.1016/j.geoderma.2009.08.025

García-Freites, S., Gough, C., & Röder, M. (2021). The greenhouse gas removal potential of bioenergy with carbon capture and storage (BECCS) to support the UK's net-zero emission target. *Biomass and Bioenergy*, *151*, 106164. https://doi.org/10.1016/j.biombioe.2021.106164

Gurevitch, J., & Hedges, L. V. (2001). Meta-analysis: Combining the results of independent experiments. In S. M. Scheiner & J. Gurevitch (Eds.), *Design and analysis of ecological experiments* (2nd ed., pp. 347–369). Oxford University Press, New York and Oxford.

Hedges, L. V., Gurevitch, J., & Curtis, P. S. (1999). The meta-analysis of response ratios in experimental ecology. *Ecology*, *80*(4), 1150–1156. https://doi.org/10.1890/0012-9658(1999)080[1150:TMAORR]2.0.CO;2

Hernandes, T. A. D., Duft, D. G., dos Santos Luciano, A. C., Leal, M. R. L. V., & Cavalett, O. (2021). Identifying suitable areas for expanding sugarcane ethanol production in Brazil under conservation of environmentally relevant habitats. *Journal of Cleaner Production*, *292*, 125318. https://doi.org/10.1016/j.jclepro.2020.125318

IEA—International Energy Agency. (2023). Biofuel Policy in Brazil, India and the United States: Insights for the Global Biofuel Alliance. https://www.iea.org/reports/biofuel-policy-in-brazil-india-and-the-united-states

IPCC (Intergovernmental Panel on Climate Change). (2019). In E. Calvo Buendia, K. Tanabe, A. Kranjc, J. Baasansuren, M. Fukuda, S. Ngarize, A. Osako, Y. Pyrozhenko, P. Shermanau, & S. Federici (Eds.), *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Published: IPCC, Switzerland.

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTest package: Tests in linear mixed effects models. *Journal of Statistical Software*, *82*(13), 1-26. https://doi.org/10.18637/jss.v082.i13

Lal, R. (2021). Soil management for carbon sequestration. *South African Journal of Plant and Soil*, *38*(3), 231–237. https://doi.org/10.1080/02571862.2021.1891474

Lapig—Laboratório de Processamento de Imagens e Geoprocessamento. (2024). Atlas das pastagens. https://atlasdaspastagens.ufg.br/

Lisboa, I. P., Cherubin, M. R., Cerri, C. C., Cerri, D. G., & Cerri, C. E. (2017). Guidelines for the recovery of sugarcane straw from the field during harvesting. *Biomass and Bioenergy*, *96*, 69–74. https://doi.org/10.1016/j.biombioe.2016.11.008

Luz, F. B., Gonzaga, L. C., Castioni, G. A. F., de Lima, R. P., Carvalho, J. L. N., & Cherubin, M. R. (2023). Controlled traffic farming maintains soil physical functionality in sugarcane fields. *Geoderma*, *432*, 116427. https://doi.org/10.1016/j.geoderma.2023.116427

Mello, F. F., Cerri, C. E., Davies, C. A., Holbrook, N. M., Paustian, K., Maia, S. M., Galdos, M. V., Bernoux, M., & Cerri, C. C. (2014). Payback time for soil carbon and sugar-cane ethanol. *Nature Climate Change*, *4*(7), 605–609. https://doi.org/10.1038/nclimate2239

Menandro, L. M. S., de Moraes, L. O., Borges, C. D., Cherubin, M. R., Castioni, G. A., & Carvalho, J. L. N. (2019). Soil macrofauna responses to sugarcane straw removal for bioenergy production. *Bioenergy Research*, *12*(4), 944–957. https://doi.org/10.1007/s12155-019-10053-2

Oliveira, D. M., Cherubin, M. R., Franco, A. L., Santos, A. S., Gelain, J. G., Dias, N. M., Diniz, T. R., Almeida, A. N., Feigl, B. J., Davies, C. A., Paustian, K., Karlen, D. L., Smith, P., Cerri, C. C., & Cerri, C. E. (2019). Is the expansion of sugarcane over pasturelands a sustainable strategy for Brazil's bioenergy industry? *Renewable and Sustainable Energy Reviews*, *102*, 346–355. https://doi.org/10.1016/j.rser.2018.12.012

Oliveira, D. M. S., Paustian, K., Davies, C. A., Cherubin, M. R., Franco, A. L. C., Cerri, C. C., & Cerri, C. E. P. (2016). Soil carbon changes in areas undergoing expansion of sugarcane into pastures in south-central Brazil. *Agriculture, Ecosystems & Environment*, *228*, 38–48. https://doi.org/10.1016/j.agee.2016.05.005

Popin, G. V., Santos, A. K., Oliveira, T. D. P., de Camargo, P. B., Cerri, C. E., & Siqueira-Neto, M. (2020). Sugarcane straw management for bioenergy: Effects of global warming on greenhouse gas emissions and soil carbon storage. *Mitigation and Adaptation Strategies for Global Change*, *25*, 559–577. https://doi.org/10.1007/s11027-019-09880-7

R Core Team. (2023). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Ramesh, T., Bolan, N. S., Kirkham, M. B., Wijesekara, H., Kanchikerimath, M., Rao, C. S., Sandeep, S., Rinklebe, J., Ok, Y. S., Choudhury, B. U., Wang, H., Tang, C., Wang, X., Song, Z., & Freeman, O. W., II. (2019). Soil organic carbon dynamics: Impact of land use changes and management practices: A review. *Advances in Agronomy*, *156*, 1–107. https://doi.org/10.1016/bs.agron.2019.02.001

Rossetto, R., Crusciol, C. A. C., Cantarella, H., Carmo, J. B., & Nascimento, C. A. C. (2018). Residues uses and environment sustainability. In R. Rossetto, C. A. C. Crusciol, H. Cantarella, J. B. Carmo, & C. A. C. Nascimento (Eds.), *Sustainable sugarcane production* (pp. 183–210). Apple Academic Press.

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

Santos, A. K. B. D., Popin, G. V., Gmach, M. R., Cherubin, M. R., Siqueira Neto, M., & Cerri, C. E. P. (2021). Changes in soil temperature and moisture due to sugarcane straw removal in central-southern Brazil. *Scientia Agricola*, *79*, e20200309. https://doi.org/10.1590/1678-992X-2020-0309

Satiro, L. S., Cherubin, M. R., Safanelli, J. L., Lisboa, I. P., da Rocha Junior, P. R., Cerri, C. E. P., & Cerri, C. C. (2017). Sugarcane straw removal effects on Ultisols and Oxisols in south-central Brazil. *Geoderma Regional*, *11*, 86–95. https://doi.org/10.1016/j.geodrs.2017.10.005

Scarpare, F. V., de Jong van Lier, Q., de Camargo, L., Pires, R. C. M., Ruiz-Corrêa, S. T., Bezerra, A. H. F., Gava, G. J. C., & Dias, C. T. S. (2019). Tillage effects on soil physical condition and root growth associated with sugarcane water availability. *Soil and Tillage Research*, *187*, 110–118. https://doi.org/10.1016/j.still.2018.12.005

Schiebelbein, B. E., Bordonal, R. D. O., Cerri, C. E. P., Oliveira, D. M. D. S., & Cherubin, M. R. (2023). Mineral-associated and particulate organic matter in aggregates as a proxy for soil C changes in pasturesugarcane land use transitions. *Revista Brasileira de Ciência do Solo*, *47*, e0220103. https://doi.org/10.36783/18069657rbcs20220103

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

Silva-Olaya, A. M., Cerri, C. E., Williams, S., Cerri, C. C., Davies, C. A., & Paustian, K. (2017). Modelling SOC response to land use change and management practices in sugarcane cultivation in south-Central Brazil. *Plant and Soil*, *410*, 483–498. https://doi.org/10.1007/s11104-016-3030-y

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

Tenelli, S., Bordonal, R. O., Cherubin, M. R., Cerri, C. E. P., & Carvalho, J. L. N. (2021). Multilocation changes in soil carbon stocks from sugarcane straw removal for bioenergy production in Brazil. *GCB Bioenergy*, *13*(7), 1099–1111. https://doi.org/10.1111/gcbb.12832

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

Van Soest, H. L., den Elzen, M. G. J., & van Vuuren, D. P. (2021). Net-zero emission targets for major emitting countries consistent with the Paris agreement. *Nature Communications*, *12*, 2140. https://doi.org/10.1038/s41467-021-22294-x

Westgate, M. J. (2019). Revtools: An R package to support article screening for evidence synthesis. *Research Synthesis Methods*, *10*(4), 606–614. https://doi.org/10.1002/jrsm.1374

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L. D. A., François, R., Grolemund, G., Hayes, A., Lionel, H., Hester, J., Kuhn, M., Lin, P., Miller, E., Bache, S. M., Müller, K., Ooms, J., Robinson, D., Seidel, D. P., Spinu, V., … Yutani, H. (2019).

Welcome to the Tidyverse. *Journal of Open Source Software*, *4*(43), 1686. https://doi.org/10.21105/joss.01686

Zani, C. F., Barneze, A. S., Robertson, A. D., Keith, A. M., Cerri, C. E., McNamara, N. P., & Cerri, C. C. (2018). Vinasse application and cessation of burning in sugarcane management can have positive impact on soil carbon stocks. *PeerJ*, *6*, e5398. https://doi.org/10.7717/peerj.5398

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Pinheiro Junior, C. R., Carvalho, J. L. N., Canisares, L. P., Cerri, C. E. P., & Cherubin, M. R. (2024). Soil carbon stocks in sugarcane cultivation: An evidence synthesis associated with land use and management practices. *GCB Bioenergy*, *16*, e13188. https://doi.org/10.1111/gcbb.13188