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RESEARCH ARTICLE

Impact of a long-term sugarcane harvesting system on crop performance, micronutrient availability, and soil organic carbon in tableland soils of Linhares-ES, Brazil

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Abstract
Unburned sugarcane harvesting has become a reality in Brazil, bringing impacts on sugarcane cultivation that are still not fully understood. This study evaluates the long-term impact (32 years) of different sugarcane harvesting systems—burned (B), unburned (U), and their alternation—on crop productivity, juice and stalk technological parameters, and soil micronutrient and organic carbon (OC) levels. The experiment, initiated in 1989, covered four cultivation cycles in Espírito Santo—Brazil. The experimental area comprised five blocks with four plots. Treatments included unburned harvesting, burned harvesting, and their alternations during the cycles. Evaluations were carried out in 2021, on the 5th ratoon of the fourth cycle. Productivity and technological quality of the juice and stalk were analyzed. Soil samples were collected at different depths and analyzed for OC content and the micronutrients B, Cu, Fe, Mn and Zn. Harvesting method combinations did not affect the productivity of dry leaves, tops, or stalks, nor the technological parameters. Average B and Fe contents were adequate, while Cu, Mn, and Zn were below recommended levels. The contents of Cu, Fe and Mn varied significantly between harvesting systems. While the harvesting systems over 32 years did not influence the productivity and technological parameters of the crop, the levels of micronutrient, except for B and Zn, and OC were affected by the different harvesting approaches. Although burned systems showed some positive responses, their continued use is not recommended due to environmental concerns. Sustainable alternatives should be prioritized to ensure long-term soil health and sugarcane viability.

Keywords Soil quality · Soil fertility · Burned harvesting · Unburned harvesting · Productivity

Introduction

The pre-harvest burning of sugarcane is a traditional practice that raises serious concerns regarding soil quality and agricultural sustainability, especially in coastal tableland soils, which are characterized by a mineralogy that results in low natural fertility. Burning alters the chemical, physical and biological composition of the soil, harming the availability of essential nutrients, which can compromise long-term productivity (Oliveira et al. 2014; Silva et al. 2021; Barros et al. 2010).

Research indicates that the burning practice can lead to annual loss of straw in amounts ranging from 10 to 30 Mg ha^{-1}. This loss compromises the maintenance of soil fertility, as straw is an important source of nutrients such as nitrogen and sulfur. This loss is influenced by factors such as the cultivar used and climatic conditions (Resende et al. 2006b; Schultz et al. 2010; Cerri et al. 2013). This loss compromises the maintenance of soil fertility, as straw is an

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important source of nutrients such as nitrogen and sulfur. This loss is influenced by factors such as the cultivar used and climatic conditions (Trivelin; Rodrigues and Victoria 1996).

In Brazil, in the 1980s, sugarcane harvesting was predominantly carried out through burning, a practice aimed at facilitating harvesting by removing straw and leaves, but resulting in serious damage to the soil. Currently, environmental legislation has promoted the adoption of unburned harvesting, which preserves soil cover and, consequently, soil quality (Moitinho et al. 2021). Unburned cropping not only reduces soil erosion but also improves soil moisture retention and biodiversity, factors that are crucial for the sustainability of agricultural production (Mkhonza and Muchaonyerwa, 2023).

Sugarcane productivity in Brazil, which has historically been below its biological potential, is often limited by low soil fertility and micronutrient deficiencies (Adorna; Crusciol and Rossato, 2013). The absorption of micronutrients, such as iron, manganese and zinc, is influenced by several factors, including plant's age and soil type. The export of micronutrients by sugarcane stalks follows a specific order, with iron being the most abundant (Orlando Filho; Rossetto and Casagrande, 2001).

Furthermore, micronutrient deficiencies can manifest themselves in disease-like symptoms, further complicating crop management. The incidence of diseases in sugarcane, which can be exacerbated by harmful management practices, is a critical factor affecting productivity (Santos 2004; Matsuoka; Garcia and Arizono, 2005). The use of resistant cultivars and balanced fertilization are recommended strategies to mitigate the effects of diseases, given that well-nourished plants tend to be more resistant. The relationship between plant nutrition and disease resistance is particularly evident in cases of boron and molybdenum deficiency, which can mimic symptoms of diseases such as Pokkah boeng (Orlando Filho; Rossetto and Casagrande, 2001).

In the long term, the evaluation of sugarcane harvesting and management systems must consider not only immediate productivity, but also the impacts on soil quality and the sustainability of the agricultural system.

This study evaluates the long-term impact (32 years) of different sugarcane harvesting systems—burned (B), unburned (U), and their alternation—on crop productivity, juice and stalk technological parameters, and soil micronutrient and organic carbon levels.

Materials and Methods

Description of the Experimental Area

The experiment was installed at Fazenda Duas Lagoas, in an area provided by Linhares Agropecuária SA in the municipality of Linhares—State of Espírito Santo, located at 19° 22′10″ S and 39° 59′30″ W (Fig. 1).

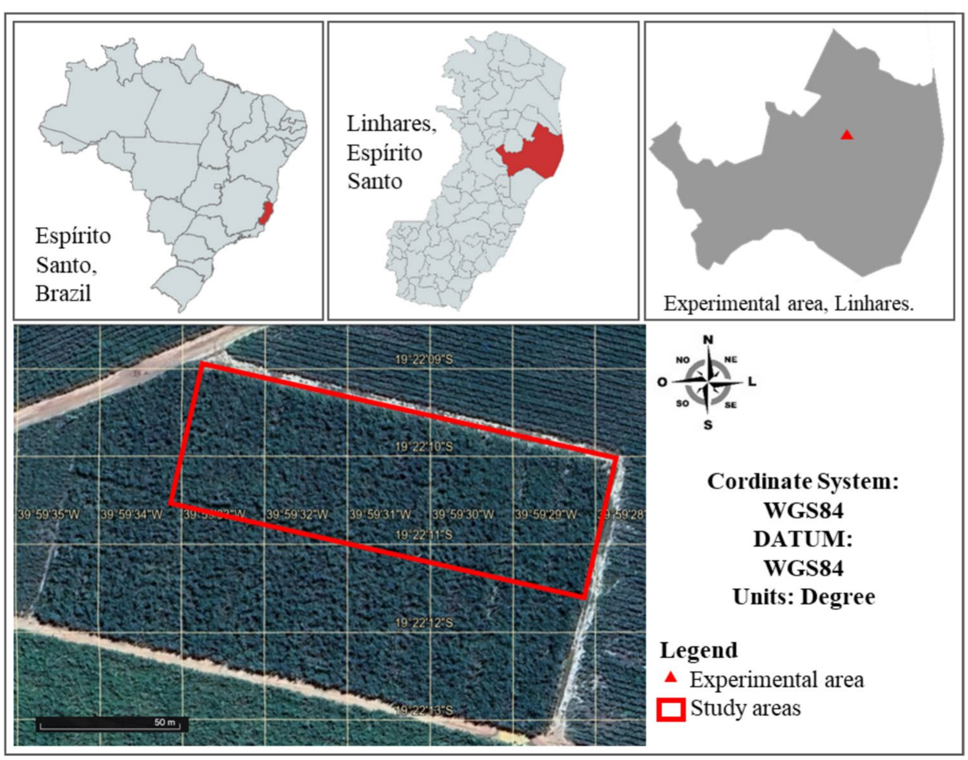

Fig. 1 Location of the experimental area, with a satellite image obtained from Google Earths Pro software

According to the Köppen classification, the region's climate is type AW, meaning a humid tropical climate with a rainy summer season and a dry winter season. The average annual rainfall of 1,250 mm and the average maximum and minimum temperatures are 29.3 and 20.6 °C, respectively. In the 2021 harvest, which was evaluated, the accumulated precipitation was 944 mm.

The area was located on tableland soil classified as Haplic Acrisol (Abruptic Hyperdytric–FAO Classification) or Dystrophic Yellow Argisol, with sandy texture according to the Brazilian classification (Ravelli Neto and Lima, 1987; Santos et al 2018; Pinheiro et al 2010). The experimental area was originally a secondary forest of the regional vegetation, cleared and initially replaced by brachiaria pasture in 1986 and, later, by sugarcane.

Treatments and Experimental Design

The experiment was implemented on May 28, 1989, making it one of the longest-lasting and most active sugarcane experiments in Brazil. The experimental design was randomized blocks, with five replications. In 2021, the plots measured 9 rows of 22 m in length, spaced 1.50 m apart, with an area of 297 m^2, constituting a total area of 5,940 m^2.

In the first cycle, the treatments were T1: unburned harvest and T2: burned harvest. In the first renewal, on 04/11/1997, the conventional soil preparation was replaced by direct planting. Direct planting consisted of destroying the ratoon using herbicides without turning the soil for the next planting.

From the second cycle onwards, two new treatments were added to the previous ones: alternation between harvesting methods across the cycles. Thus, the treatments were constituted as follows in the fourth cycle: T1: unburned harvest where unburned cane was harvested throughout all cycles (UUUU); T2: burned harvest where burned cane was harvested throughout all cycles (BBBB); T3: alternate harvest starting with unburned harvest, the first cycle was unburned cane, the second burned, the third unburned and the fourth burned (UBUB); and T4: alternate harvest starting with burned harvest where the first cycle was burned cane, the second unburned, the third burned and the fourth unburned (BUBU). The experimental area usage history, harvest system treatments, and management time can be seen in Table 1. The following cultivars were used: RB739735 in the 1st and 2nd Cycles, SP79-1011 in the 3rd Cycle and RB965917 in the 4th Cycle.

Culture Cycles Over 32 Years

This study was conducted over 32 years (1989–2021) in four sugarcane cultivation cycles: 1989–1996 (1st cycle), 1997–2004 (2nd cycle), 2005–2014 (3rd cycle) and 2015–2021 (4th cycle). In each cycle, several harvests were carried out, totaling 7 harvests in the 1st and 2nd cycles, 9 harvests in the 3rd cycle and 6 harvests in the 4th cycle, as detailed below.

1st Cycle (1989–1996)—The cultivar used was RB739735, planted in May 1989, with seedlings from the plant's nursery, 10 months old at planting. The planting was carried out in furrows 0.30 m deep and 1.20 m apart. Soil preparation included deep plowing and harrowing. Soil correction and fertilization were applied uniformly across the experiment, according to the sugar mill's recommendations based on soil analysis. The sugarcane plant was harvested in September 1990, with six subsequent ratoons harvested

Table 1 Harvesting system treatments regarding straw management throughout the sugarcane cultivation cycles, applied over time, on coastal tableland soil, in the municipality of Linhares-ES

Management time	1st cycle		2nd cycle		3rd cycle	4th cycle
	1989–1996		1997–2004		2005–2014	2015–2021
32 years old U	T1	U	T1	UU	UUU	UUUU
7 years U-8 years B			T3	UB	UBU	UBUB
10 years U-7 years B						
32 years old B	T2	B	T2	BB	BBB	BBBB
7 years B-8 years U			T4	BU	BUB	BUBU
10 years B-7 years U						
Soil Preparation	Conventional Preparation		Direct Planting		Direct Planting	Direct Planting
Cultivate	RB739735		RB739735		SP79-1011	RB965917
Spacing	1.2 m		1.2 m		1.3 m	1.5 m

U: unburned cane harvest, *B*: burned cane harvest, *UU*: unburned-unburned cane harvest, *UB*: unburned-burned cane harvest, *BB*: burned-burned cane harvest, *BU*: burned-unburned cane harvest, *UUU*: burned-burned-burned cane harvest, *UBU*: unburned-burned-unburned cane harvest, *BBB*: burned-burned-burned cane harvest, *BUB*: burned-unburned-burned cane harvest, UUUU: unburned-unburned-unburned-unburned cane harvest, *UBUB*: unburned-burned-unburned-burned cane harvest, *BBBB*: burned-burned-burned-burned cane harvest, *BUBU*: burned-unburned-burned-unburned cane harvest until 1996. All harvests were done manually, without the use of heavy machinery.

2nd Cycle (1997–2004)—The first renewal of the experiment was carried out in April 1997 with the elimination of the ratoon crop by applying glyphosate. Direct planting was adopted, with furrowing performed between the rows of the previous cycle (spacing of 1.20 m). The cultivar RB739735 was replanted, and the planting and ratoon fertilization followed the doses defined by the sugar mill based on soil analysis, applied uniformly across the entire experiment. The harvests were manual, with the first harvest conducted in September 1998, followed by annual ratoon harvests until 2004.

3rd Cycle (2005–2014)—The third cycle began with the elimination of ratoons in February 2005. Direct planting was maintained, with a spacing of 1.30 m between furrows and a depth of 0.30 m. The cultivar SP79-1011 was used in this cycle. Planting and ratoon fertilization followed the protocol used by the sugar mill, applied uniformly across the experiment. Manual harvesting of the sugarcane plant was carried out in August 2006, and subsequent harvests were carried out until October 2014, totaling 9 harvests.

4th Cycle (2015–2021)—The last cycle began in February 2015 with direct planting of the cultivar RB965977. The furrow depth was maintained at 0.30 m, with a spacing of 1.50 m between furrows. Planting and ratoon fertilization were carried out, following the same doses recommended by the sugar mill. The sugarcane plant was harvested in August 2016, and the ratoon crops were harvested manually until September 2021, with a total of 6 harvests in this cycle.

Assessments Carried Out

In the plots, samples were taken from two random and representative points along the central rows, measuring two linear meters, with the entire plant being cut close to the ground to evaluate productivity. After this, three stems were selected from each sample to analyze the technological parameters.

The plants collected in the sampling were separated into stems, tips (heart of palm and green leaves) and dry leaves (sugarcane straw) and then, weighed. The fresh mass productivity (Mg ha $^{-1)}$ of these parts was determined.

The following technological parameters of the juice and sugarcane were determined: percentage of total soluble solids of the juice (°Brix); percentage of sugar cane fibers (%); Pol of the juice (%); purity of the juice (%); reducing sugars—AR (%) and total recoverable sugars—ATR (kg t $^{-1}$).

Soil samples were taken at depths of 0–0.05; 0.05–0.1; 0.1–0.2; 0.2–0.3; 0.3–0.4 m.

The identified samples were taken to the laboratory, where they were air-dried, crushed and sieved, through a 2.0 mm mesh to obtain air-dried fine soil. The samples were then used to determine boron (B), copper (Cu), iron (Fe), manganese (Mn), zinc (Zn) and organic carbon (OC).

The analyses for determining the micronutrients Cu, Fe, Mn, Zn and OC were conducted following the methods described in the Manual of Soil Analysis Methods (Teixeira et al 2017).

The determination of B levels was performed as described by Berger and Truog (1939) with modifications. For this procedure, 10 mL of soil were mixed with 20 mL of deionized water in a 135 mL Erlenmeyer flask, and the mixture was heated to boiling for 2 min. After cooling to room temperature, 2 mL of 0.1 M $CaCl_2$ was added and the mixture was allowed to rest for 12 h. Then, 1 mL of the solution was transferred to plastic bottles, and 4 mL of curcumin solution was added. The bottles were heated in a water bath at 65 °C until dry, followed by an additional 15 min of heating. After cooling, 25 mL of 95% ethyl alcohol was added and the filtrate was analyzed by spectrophotometry at 540 nm.

Statistical Analysis

The data were subjected to normality (Shapiro–Wilk) and homogeneity of variances tests (Barllet). The results were analyzed for variance using the F test, and the mean values were compared using the Duncan's multiple range test at a 5% significance level. The R software was used to perform the calculations and statistical analyses.

Results

Productivity and Technological Analysis

Table 2 shows the average productivity of dry leaves, tips and stalks harvested at the end of the fourth productive cycle of the experiment, in the 2020/2021 harvest (5th ratoon). The experiment, carried out over 32 years, evaluated the influence of different harvesting systems, including unburned harvest (UUUU), burned harvest (BBBB) in all cycles, and alternating harvests of unburned–burned–unburned–burned sugarcane (UBUB) and burned–unburned–burned–unburned harvest (BUBU).

No statistically significant differences were observed between treatments for the production of dry leaves, tips and stems, as shown in Table 2.

The values of the technological parameters for the different treatments are presented in Table 3. It was observed that the sugarcane harvest systems, whether burned or unburned, applied exclusively or alternately throughout the crop cycles, did not cause significant differences in these parameters. These results indicate that maintaining the straw in the unburned harvest presents a technological performance similar to the burning practice.

Table 2 Productivity of dry leaves, tips and stems (in Mg ha^{-1}), of the sugarcane cultivar RB965917 in 5th ratoon, under different harvesting systems over 32 years, in the 2020/2021 harvest, in Yellow Argisol

Treatment	Dry leaves Mg ha^{-1}	Pointer	Thatch
UUUU	5.80a	12.27a	70.37a
UBUB	5.45a	12.78a	70.00a
BUBU	6.73a	13.20a	67.22a
BBBB	6.55a	11.68a	67.46a
Overall average	6.13	12.48	68.04
CV	23.33	18.91	23.29

Averages followed by the same letter do not differ statistically from each other according to Duncan's test (prob < 0.5). UUUU: All cycles with unburned cane harvest; UBUB: Alternating cycles with unburned–burned–unburned–burned cane harvest; BUBU: Alternating cycles with burnt–unburned–burned–unburned cane harvest; BBBB: All cycles with burnt cane harvest

Table 3 Technological parameters of the juice and stalk evaluated from the sugarcane cultivar RB965917 in the 5th ratoon, under different harvesting systems over 32 years, in the 2020/2021 harvest, in Yellow Argisol

Treatment	°Brix	Fibers (%)	Pol	Purity (%)	AR (%)	ATR (kg t^{-1})
UUUU	22.15a	14.50a	18.48a	83.38a	0.78a	154.19a
UBUB	22.85a	14.77a	19.21a	84.08a	0.76a	159.51a
BUBU	21.57a	14.33a	17.87a	82,83a	0.80a	149.70a
BBBB	22.35a	14.25a	18.63a	83.35a	0.78a	155.77a
Average	22,23	14.46	18.55	83.41	0.78	154.79
CV (%)	3.82	3.80	4.66	0.89	3.57	4.12

Averages followed by the same letter do not differ statistically from each other according to Duncan's test (prob < 0.5). *UUUU*: All cycles with unburned cane harvest; *UBUB*: Alternating cycles with unburned–burned–unburned–burned cane harvest; *BUBU*: Alternating cycles with burnt–unburned–burned–unburned cane harvest; *BBBB*: All cycles with burnt cane harvest

Micronutrients and Soil Organic Carbon

The results of chemical analyses of micronutrients and soil organic carbon (OC) at different depths (0–0.05; 0.05–0.1; 0.1–0.2; 0.2–0.3; 0.3–0.4 m), after 32 years of experimentation, indicate that the applied treatments significantly influenced the average contents of Cu, Fe, Mn and OC at least at one of the depths evaluated (Table 4). The contents of B and Zn, however, did not present remarkable variations due to the treatments.

Although B levels did not vary substantially, it was observed that treatments with alternating cycles resulted in higher levels of this element in the soil compared to the ones without alternation (Fig. 2a).

For Cu, harvesting carried out exclusively unburned or burned (UUUU or BBBB) resulted in significantly higher values at depths of 0–0.05, 0.05–0.1 and 0.3–0.4 m (Table 4), with the BUBU treatment not differing from the other treatments at the last depth (Fig. 2b).

Regarding Fe, the BBBB treatment differed from the alternating treatments (UBUB and BUBU), being similar to the UUUU treatment in the most superficial layer (0–0.05 m) (Table 4). However, the UBUB treatment presented higher Fe contents at greater depths (Fig. 2c).

Mn had the highest content in the BUBU treatment, differing from the UBUB between 0.2–0.3 m and from the other treatments between 0.3–0.4 m (Table 4). Overall, the UBUB treatment presented the highest Mn contents throughout the soil profile (Fig. 2d).

No difference was observed between treatments regarding Zn levels throughout the soil profile (Fig. 2e).

The micronutrients Cu and Fe showed significant responses in the surface layers (0–0.05 m), while Fe and Mn stood out at greater depths (0.3–0.4 m) (Fig. 2b–d).

The OC content was higher in the unburned treatment (UUUU) compared to the treatments with alternating cycles (UBUB and BUBU) at depths of 0–0.05, 0.05–0.1 and 0.2–0.3 m, but did not differ from the BBBB treatment (Table 4). However, the BBBB treatment tended to present higher OC levels than the alternating treatments at all depths, except between 0.1–0.2 m. The UUUU treatment presented the highest OC values throughout the soil profile (Fig. 2f).

Table 4 Boron, copper, iron, manganese, zinc and organic carbon contents of a Yellow Argisol, under different sugarcane harvesting systems, at depths of 0–0.05; 0.05–0.1; 0.1–0.2; 0.2–0.3 and 0.3 to 0.4 m

Treat	B	Cu	Fe	Mn	Zn	OC
	mg kg^{-1}					g kg^{-1}
	0 to 0.05 m					
UUUU	0.37a	0.45a	84.40ab	4.37a	0.77a	30.12a
UBUB	0.58a	0.25b	112.16a	5.08a	0.90a	12.23bc
BUBU	0.64a	0.22b	112.39a	7.78a	0.65a	8.86c
BBBB	0.40a	0.52a	70.26b	5.29a	0.83a	21.17ab
CV%	32,33	34.18	21.81	45.23	36.26	45.08
	0.05 to 0.1 m					
UUUU	0.45a	0.38a	96.18a	2.08a	0.28a	24.28a
UBUB	0.56a	0.22b	133.87a	2.06a	0.43a	11.08b
BUBU	0.58a	0.14b	129.14a	3.55a	0.24a	9.85b
BBBB	0.44a	0.46a	93.90a	4.05a	0.41a	20.69a
CV%	22:30	37.14	28.18	52.99	34.77	39.22
	0.1 to 0.2 m					
UUUU	0.48a	0.48a	104.40a	1.99a	0.23a	11.99a
UBUB	0.52a	0.19a	138.14a	0.39a	0.31a	9.41a
BUBU	0.52a	0.32a	118.52a	3.34a	0.22a	7.87a
BBBB	0.40a	0.45a	108.42a	1.90a	0.18a	9.37a
CV%	29.69	91.36	51.20	93.50	58.14	23:30
	0.2 to 0.3 m					
UUUU	0.40a	0.51a	133.66a	1.17ab	0.13a	18.30a
UBUB	0.51a	0.15a	213.13a	0.37b	0.23a	9.99b
BUBU	0.59a	0.27a	132.86a	4.94a	0.26a	9.31b
BBBB	0.44a	1.19a	117.13a	1.26ab	0.17a	17.84a
CV%	21.26	190.44	78.27	115.32	40.02	34.02
	0.3 to 0.4 m					
UUUU	0.52a	0.40a	189.35a	0.91b	0.15a	15.41a
UBUB	0.60a	0.12b	287.32a	0.33b	0.22a	9.12a
BUBU	0.53a	0.18ab	188.68a	2.30a	0.19a	8.85a
BBBB	0.51a	0.38a	139.39a	1.32b	0.12a	14.94a
CV%	15.86	60.72	40.09	56.59	45.96	36.14

Averages followed by the same letter do not differ statistically from each other according to Duncan's test (prob < 0.5). *UUUU*: All cycles with unburned cane harvest; *UBUB*: Alternating cycles with unburned–burned–unburned–burned cane harvest; *BUBU*: Alternating cycles with burnt–unburned–burned–unburned cane harvest; *BBBB*: All cycles with burnt cane harvest

Discussion

In this study, sugarcane productivity did not show significant differences between the burned and unburned harvesting systems, reinforcing the recommendation of unburned sugarcane harvesting due to its agronomic and environmental benefits. Resende et al. (2006a) showed that unburned sugarcane increased sugar production by 21.5% compared to burned harvesting over 14 harvests. Pinheiro et al. (2010) and Tavares et al.. (2010) also found no significant differences in productivity, although unburned sugarcane showed slight superiority in some cases. Thus, unburned harvesting is a sustainable and efficient alternative.

Long-term studies, such as those conducted by Resende et al. (2006b), emphasize the importance of straw in recycling nutrients and its beneficial effect on productivity over time. The gradual decomposition of straw favors the release of nutrients in a sustainable manner, which, according to the authors, contributes to a 25% higher productivity in systems with unburned harvesting in a 15-year experiment with 13 harvests.

The average productivity obtained in this study was higher than the state average for this harvest (56.65 Mg ha^{-1}), especially in the treatment with unburned

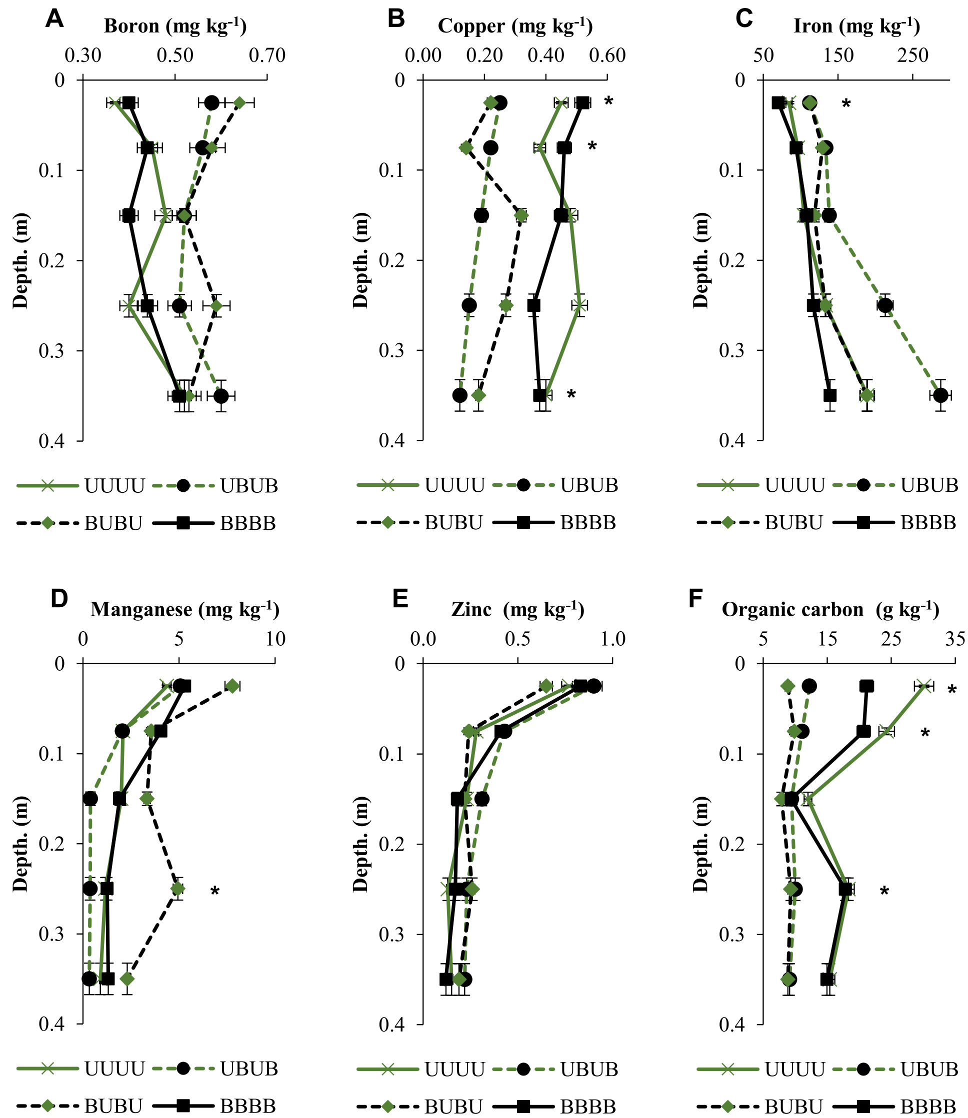

Fig. 2 Average contents of boron **a**, copper **b**, iron **c**, manganese **d**, zinc **e** and organic carbon **f** in the soil, in the layers of 0–0.05; 0.05–0.1; 0.1–0.2; 0.2–0.3; 0.3–0.4 m, under different sugarcane harvest systems, in Yellow Argisol, in Linhares-ES. *: At these depths, the treatments showed significant differences according to the Duncan's multiple range test at 5%. UUUU: unburned-unburned-unburned-unburned cane harvest, UBUB: unburned-burned-unburned-burned cane harvest, BBBB: burned-burned-burned-burned cane harvest, BUBU: burned-unburned-burned-unburned cane harvest

harvest. This result is particularly relevant, considering that the experiment is in its final phase, in the 5th ratoon.

Regarding the technological parameters, the harvesting systems, whether burned, unburned or their alternation, did not result in significant differences in the attributes analyzed. A similar behavior was observed by Resende et al. (2006a), who only noted an effect in treatments with nitrogen fertilization.

Regarding micronutrients, studies such as those by Canellas et al. (2003) and Souza et al. (2012) demonstrate the positive impact of maintaining straw on the retention of organic carbon and the availability of nutrients in the soil, such as Fe, Cu, Zn and Mn. Straw acts as a source of nutrients, and contributes to the formation of humified organic matter, improving soil quality and its productive capacity. The increase in the amount of organic carbon and micronutrients, as observed in soils with 55 years of unburned cultivation, highlights the role of straw as a soil conditioning agent, promoting improvements in the nutrients supply and in the physical structure of the soil (Canellas et al. 2003).

The average levels found for micronutrients were adequate for B and very high for Fe, while for Cu, Mn and Zn they were very low (Quaggio et al 2022; Prezotti et al 2007). Based on this result, fertilization with Cu, Mn and Zn can be recommended. The average OC content found was 14.03 g kg^{-1} and can be interpreted as average, based on information from Freire et al. (2013).

Resende et al. (2006b) and Mendonça et al. (2000) highlight that straw can increase the fulvic acids and humin fraction in organic matter, suggesting that, over time, the preservation of straw leads to the condensation of alkaline-soluble fractions, enhancing the quality of organic matter and contributing to the sustainability of the production system.

These findings indicate that straw preservation not only favors the productivity and sustainability of the sugarcane cultivation system, but also plays a crucial role in maintaining and improving soil quality, especially in tropical regions where intensive weathering and low fertility are constant challenges.

Conclusions

The yields of dry leaves, tips and stalks do not show significant variation across different sugarcane harvesting systems, whether unburned or burned, applied exclusively or alternately throughout the cycles. Similarly, no relevant differences were observed in the technological parameters evaluated. However, alternating harvesting systems tends to increase soil B levels. In contrast, Cu levels are higher when the same harvesting system is consistently applied, regardless of whether it is unburned or burned cane. On the other hand, the continuous burned harvesting system (BBBB) results in the lowest Fe levels in the soil. The alternation between BUBU favors higher Mn levels, while Zn levels are not affected by the harvesting system throughout the four cycles evaluated. Finally, the exclusively unburned (UUUU) or burned (BBBB) harvesting systems promote higher organic carbon levels in the soil.

These findings provide valuable insights into the long-term effects of different management practices on sugarcane cultivation. While certain soil properties and crop responses were positively influenced under burned conditions, these benefits should be interpreted with caution. The environmental and regulatory constraints surrounding sugarcane burning make this practice increasingly unsustainable and undesirable. Therefore, alternative management strategies that enhance soil health and productivity while minimizing negative environmental impacts should be prioritized.

Future research should focus on sustainable cultivation practices that do not rely on burning, such as green cane harvesting and improved soil conservation techniques. Transitioning to these environmentally responsible approaches will ensure the long-term viability of sugarcane production while aligning with modern agricultural and environmental policies. Ultimately, the phase-out of sugarcane burning is not only a necessity but also an opportunity to implement more sustainable and productive management systems.

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Author contributions Conceptual idea: Lima, E; Silva, GLS; Methodology design: Lima, E; Silva, GLS; Data collection: Lima, E; Silva, GLS; Data analysis and interpretation: Silva, GLS; Lima, E; Carmo, MGF, and Writing and editing: Silva, GLS; Lima, E; Carmo, MGF.

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Data availability The authors make data from this study available upon request.

Declarations

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

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Consent for publication All the authors have their own contribution in writing of this article.

References

Adorna, J.C., C.A.C. Crusciol, and O.B. Rossato. 2013. Fertilization with filter cake and micronutrients in plant cane. *Revista Brasileira De Ciência Do Solo* 37 (3): 649–657. https://doi.org/10.1590/S0100-06832013000300011.

Barros, R.P., P.R.A. Viégas, T.L. Silva, R.M. Souza, L. Barbosa, R.A. Viégas, M.C.V. Barretto, and A.S. Melo. 2010. Alterações em atributos químicos de solo cultivado com cana-de-açúcar e adição de vinhaça. *Pesquisa Agropecuária Tropical* 40 (3): 341–346. https://doi.org/10.5216/pat.v40i3.6422.

Berger, K.C., and E. Truog. 1939. Boron determination insoils and plantas using the quinalizarin reaction. *Ind. Eng. Chem* 11:540–545.

Canellas, L.P., A.C.X. Velloso, C.R. Marciano, J.F.G.P. Ramalho, V.M. Rumjanek, C.E. Rezende, and G.A. Santos. 2003. Propriedades químicas de um Cambissolo cultivado com cana-de-açúcar, com preservação do palhiço e adição de vinhaça por longo tempo. *Revista Brasileira De Ciência Do Solo* 27 (5): 935–944. https://doi.org/10.1590/S0100-06832003000500018.

Cerri, C.E.P., M.V. Galdos, J.L.N. Carvalho, B.J. Feigl, and C.C. Cerri. 2013. Quantifying soil carbon stocks and greenhouse gas fluxes in the sugarcane agrosystem: Point of view. *Scientia Agricola* 70 (5): 361–368. https://doi.org/10.1590/S0103-90162013000500011.

Freire, L.R., D.V.B. Campos, L.H.C. Anjos, E. Zonta, M.G. Pereira, R.M. Bloise, G.N.C. Moreira, and P.A. Eira. 2013. Análise química de amostra de terra. In *Manual de calagem e adubação do Estado do Rio de Janeiro*, ed. L.R. Freire, et al. Brasil: Universidade Rural.

Matsuoka, S., A.A.F. Garcia, and H. Arizono. 2005. Melhoramento da cana-de-açúcar. In *Melhoramento de espécies cultivadas*, ed. A. Borém. Viçosa: UFV.

Mendonça, H.N.S., E. Lima, L.H.C. Anjos, L.A. Silva, M.B. Ceddia, and M.V.M. Antunes. 2000. Propriedades químicas e biológicas de solo de tabuleiro cultivado com cana-de-açúcar com e sem queima da palhada. *Revista Brasileira De Ciência Do Solo* 24:201–207. https://doi.org/10.1590/S0100-06832000000100022.

Mkhonza, N.P., and P. Muchaonyerwa. 2023. Organic carbon and microbial activity in Umbric Rhodic Ferralsol soils under green cane relative to pre-harvest burning of sugarcane. *Journal* *of Soils and Sediments* 23:804–816. https://doi.org/10.1007/s11368-022-03358-x.

Moitinho, M.R., A.S. Ferraudo, A.R. Panosso, E.S. Bicalho, D.B. Teixeira, M.A. Barbosa, S.M. Tsai, B.M.F. Borges, F.S. Cannavan, J.A.M. Souza, and N. La Scala. 2021. Effects of burned and unburned sugarcane harvesting systems on soil CO2 emission and soil physical, chemical, and microbiological attributes. *CATENA* 196:104903. https://doi.org/10.1016/j.catena.2020.104903.

Oliveira, A.P.P., E. Lima, L.H.C. Anjos, E. Zonta, and M.G. Pereira. 2014. Sistemas de colheita da cana-de-açúcar: Conhecimento atual sobre modificações em atributos de solos de tabuleiro. *Revista Brasileira De Engenharia Agrícola e Ambiental* 18 (9): 939–947. https://doi.org/10.1590/1807-1929/agriambi.v18n09p939-9477.

Orlando Filho, J., R. Rosseto, and A.A. Casagrande. 2001. Cana-de-açúcar. In *Micronutrientes e elementos tóxicos na agricultura*, ed. M.E. Ferreira, M.C.P. Cruz, B.V. Raij, and C.A. Abreu. Jaboticabal: CNPq/FAPESP/POTAFOS.

Pinheiro, E.F.M., E. Lima, M.B. Ceddia, S. Urquiaga, B.J.R. Alves, and R.M. Boddey. 2010. Impact of pre-harvest burning versus trash conservation on soil carbon and nitrogen stocks on a sugarcane plantation in the Brazilian Atlantic forest region. *Plant and Soil* 333:71–80. https://doi.org/10.1007/s11104-010-0320-7.

Prezotti, L.C., J.A. Gomes, G.G. Dadalto, and J.A. Oliveira. 2007. *Manual de Recomendação de Calagem e Adubação para o Estado do Espirito Santo – 5ª aproximação*. Vitória: SEEA/INCAPER/CEDAGRO.

Quaggio, J.A., et al. 2022. Cana-de-açúcar. In *Boletim 100 Recomendações de adubação e calagem para o estado de São Paulo*, ed. H. Cantarella, et al. Campinas: Instituto Agronômico.

Ravelli Neto, A. and E. Lima. 1987. Caracterização de uma topossequência de solos sobre sedimentos do terciário e quaternário em Linhares-ES. In: CONGRESSO BRASILEIRO DE CIÊNCIA DO SOLO, 21., 1987, Campinas. *Programas e resumos*. Campinas: SBCS, p. 166.

Resende, A.S., A. Santos, R.P. Xavier, C.H. Coelho, A. Gondim, O.C. Oliveira, B.J.R. Alves, R.M. Boddey, and S. Urquiaga. 2006a. Efeito da queima da palhada da cana-de-açúcar e de aplicações de vinhaça e adubo nitrogenado em características tecnológicas da cultura. *Revista Brasileira De Ciência Do Solo* 30:937–941. https://doi.org/10.1590/S0100-06832006000600003.

Resende, A.S., R.P. Xavier, O.C. Oliveira, S. Urquiaga, B.J.R. Alves, and R.M. Boddey. 2006b. Long-term effects of pre-harvest burning and nitrogen and vinasse applications on yeld of sugar cane and soil carbon and nitrogen stocks on a plantation in Pernambuco, N.E Brazil. *Plant and Soil* 281:3339–3351. https://doi.org/10.1007/s11104-005-4640-y.

Santos, H.G., P.K.T. Jacomine, L.H.C. dos Anjos, V.A. Oliveira, J.F. Lumbreras, M.R. Coelho, J.A. Almeida, J. C. Araujo Filho, J.B. Oliveira, and T.J.F. Cunha. 2018. *Sistema brasileiro de classificação de solos*. 5. ed. rev. e ampl.. Rio de Janeiro: EMBRAPA Solos, 356 p.

Santos, A.S. 2004. *Doenças causadas por fungos e bactérias em cana-de-açúcar*. Comunicado Técnico. https://www.agencia.cnptia.embrapa.br/Repositorio/santos1_000fxf33mr802wyiv80soht9hf2cc25l.pdf. Accessed: January 18, 2024.

Schultz, N., E. Lima, M.G. Pereira, and E. Zonta. 2010. Efeito residual da adubação na cana-planta e da adubação nitrogenada e potássica na cana-soca colhidas com e sem a queima da palhada. *Revista Brasileira De Ciência Do Solo* 34:811–820. https://doi.org/10.1590/S0100-06832010000300023.

Silva, R., R. Silva, J. Souza, J. Souza, and T. Gedijesk. 2021. Um estudo de caso da remoção da palhada de cana-de-açúcar do solo: quais são as implicações no conteúdo de matéria orgânica do solo? *Research Society and Development* 10 (14): e71101421717. https://doi.org/10.33448/rsd-v10i14.21717.

Souza, G.S., Z.M. Souza, R.B. Silva, F.S. Araújo, and R.S. Barbosa. 2012. Compressibilidade do solo e sistema radicular da cana-de-açúcar em manejo com e sem controle de tráfego. *Pesquisa Agropecuária Brasileira* 47 (4): 603–612. https://doi.org/10.1590/S0100-204X2012000400017.

Tavares, O.C.H., E. Lima, and E. Zonta. 2010. Crescimento e produtividade da cana planta cultivada em diferentes sistemas de preparo do solo e de colheita. *Acta Scientiarum. Agronomy* 32 (1): 61–68. https://doi.org/10.4025/actasciagron.v32i1.2051.

Teixeira, P.C., G.K. Donagemma, A. Fontana, and W.G. Teixeira. 2017. *Manual de métodos de análise de solo*, 3rd ed. Brasília: Embrapa.

Trivelin, P.C.O., J.C.S. Rodrigues, and R.L. Victoria. 1996. Utilização por soqueira de cana-de-açúcar de início de safra do nitrogênio da aquamônia-15N e uréia-15N aplicado ao solo em complemento à vinhaça. *Pesquisa Agropecuária Brasileira* 31(2): 89–99. https://seer.sct.embrapa.br/index.php/pab/article/view/4457/1743 Accessed: February 8, 2024.