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Sugarcane Row Gaps Assessment over Successive Burned and Unburned Annual Harvests

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Abstract: Mechanized harvesting operations promote a series of benefits to sugarcane production but are also a cultivation step responsible for developing a series of problems for the soil and the plants due to plant mechanical damage, resulting in a decline in production over successive cycles due to row gaps emergence. The objective of this study was to evaluate the impact of burned and unburned harvesting systems on the occurrence of sugarcane row gaps over annual harvests. For this study, a burned and an unburned area were selected. The row gap number and length (sum of gaps, m) were measured after the sugarcane planting and plant-cane cultivation stages and after the first, second, and third sugarcane ratoon harvests. The results revealed that there was no difference in the number and length of row gaps between the burned and unburned harvesting systems. However, the row gap number and length considerably increased after the second harvest in both treatments (burned and unburned). The row gap number and length were close to 5 and 1–5 m at the planting and plant-cane cultivation stages and increased to around 60 and 70 m as the harvest progressed, respectively, in burned and unburned harvesting. Our results suggest that row gaps in sugarcane fields are independent of the burned or unburned sugarcane harvesting system but increase as the number of harvests increases.

Keywords: crop spacing; machinery traffic; sugarcane ratoon

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1. Introduction

Brazil is one of the largest sugarcane producers in the world, with current production at around 757 million tons [1]. Sugarcane crop has an annual cycle, in which after the first harvest, the plants are harvested for five to seven agricultural years [2]. In this sense, sugarcane harvesting systems play an important role in ensuring the quality and quantity of production [3].

Most of the sugarcane in Brazil (approximately 91%) is currently harvested using the mechanized green harvest, without the use of burning [4]. This percentage has increased over the years due to the benefits of this type of harvesting, such as greater agility in harvesting, a decrease in pre-burning in the field, gas emission reduction, and an increase in efficiency, with a reduction in harvesting time [5].

Although there is a continuous conversion from the burned system to the unburned system, topography and social aspects still make burning predominant in the Northeastern region of Brazil, which represents approximately 10% of national production [4]. In this production system, sugarcane is burned, manually cut, and then mechanically collected by tractors, trucks, and trailers to be transported to the industry [6–10].

Whether through fully unburned or through burned harvesting, it is worth noting that an important requirement for high productivity is good uniformity of the sugarcane plantation and ratoon regrowth, which may be damaged due to gaps that emerge at plant rows caused by planting errors, impairment during harvesting, machine traffic, pests, and diseases, among other factors [11,12]. These gaps can reduce the sugarcane stalk yield when they reach a high level [12]. These processes can be observed and measured directly, making it possible to study the impact of harvesting systems on the plant.

It has been observed that agricultural machinery used during the harvesting stage is mainly responsible for the emergence of gaps as the sugarcane plantation ages [13]. In this regard, ref. [14,15] reported a substantial decline in sugarcane productivity that has been observed since the time when mechanization was intensified.

Unburned harvesting can cause damage to the base of the plant, which significantly reduces sprouting and facilitates pest and disease attacks [16–18]. During unburned harvesting, sugarcane damage can occur to the plants, such as uprooting, root disturbance, and stem trampling, which can be a major cause of reduced production and a decline in product quality [19–21].

Thus, the identification and quantification of gaps due to mechanization impacts are of great importance, as they allow for the evaluation of germination and tillering uniformity and, consequently, the formation of stems, which are variables directly correlated with productivity [11,22–24]. However, studies that evaluate the occurrence of row gaps in sugarcane fields are sparse in the literature. In this context, we hypothesize that row gaps increase with successive sugarcane harvests after planting due to machinery impacts. Thus, the objective of this study was to evaluate the impact of burned and unburned harvesting systems on the occurrence of row gaps in sugarcane cultivation during the production cycle.

2. Materials and Methods

2.1. Study Site Characteristics

The study was conducted at Usina São José, located in the municipality of Igarassu in the North Zona da Mata region of the state of Pernambuco, Brazil (7°49′12.90″ S latitude and 35°0′39.18″ W longitude). The soil of the area is classified as a sandy-loam Ultisol according to [25] (Table 1). The climate of the region, according to the Köppen classification, is of the "AS" type, which is a rainy tropical climate [26], with an average annual precipitation of 1500 mm and an average annual temperature of 25 °C.

Table 1. Basic soil physical characterization of the experimental site cultivated with sugarcane.

Characterization	Sugarcane Areas	
Soil class	Ultisol	
Particle density (g cm^{-3})	2.63	
Layer (m)	0–0.20	0.20–0.40
Soil texture	Sandy loam	Sandy loam
Sand (%)	83	79
Silt (%)	9	9
Clay (%)	8	12
Organic carbon (g kg^{-1})	17.0	12.0
Bulk density (g cm^{-3})	1.65	1.71

Two areas with dimensions of 100 × 100 m were delimited within a plot of 18 ha, with unburned harvests conducted in the first area (A) and burned harvests conducted in the second area (B) (Figure 1).

Both unburned and burned areas received conventional soil tillage, characterized by the use of a subsoiler up to 0.4 m, a disk harrow at 0.20 m depth, and one pass with a leveling disc harrow. After soil preparation, sugarcane planting (15/02/2018) was carried out using 12 t·ha^{-1} of sugarcane stems, variety RB92579, with a combined spacing of 0.90 × 1.40 m (Figure 1).

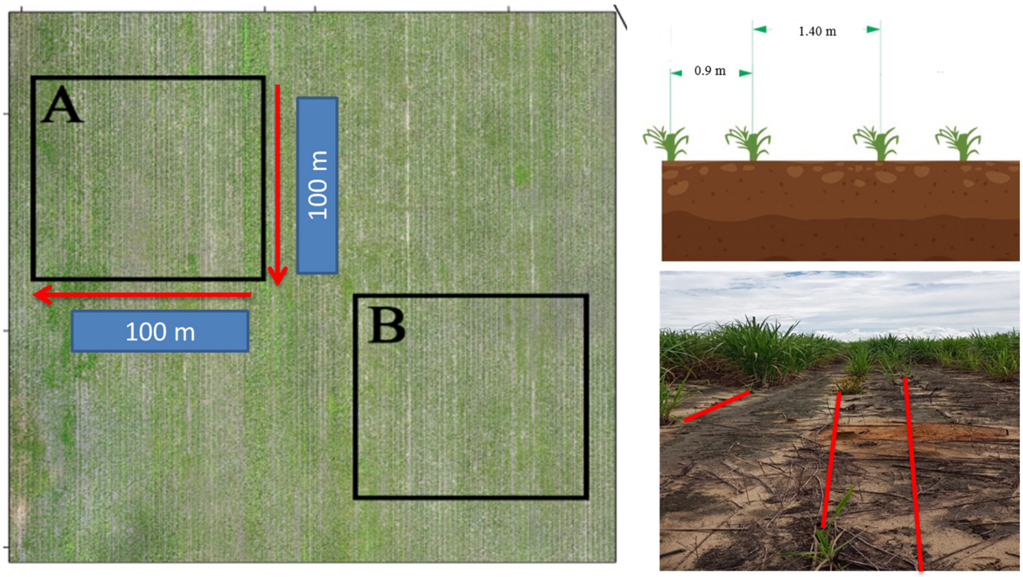


Figure 1. Representation of crop planting positions and sampling protocol. Areas subjected to unburned (**A**) and burned (**B**) harvest systems. Red lines represent gaps.

Two techniques were used during the harvesting stages: unburned and burned. The unburned system involves the use of machine harvesters, tractors, and transfer equipment, where sugarcane cutting is carried out without burning, i.e., green harvest. The burned harvesting system involves the use of manual cutting with subsequent mechanical collection using conventional loaders and tractors, trucks, and trailers for transportation.

2.2. Measuring Sugarcane Row Gaps

Twelve planting rows were selected (Figure 2) to monitor the evolution of gaps throughout the experimental period. In each of the areas (unburned and burned), row gaps were evaluated in the corresponding periods after sugarcane planting (P-CH), after the plant-cane harvest (1RH), after the first ratoon harvest (2RH), after the second ratoon harvest (3RH), and after the third ratoon harvest (4RH) (Table 2).

Especially in the plant-cane harvest, 1RH, sugarcane in both areas was harvested without burning for both the burned and unburned harvest systems. From 2RH onwards, the burned area received burning, manual cutting, and machine loading, while the unburned area continued to be harvested without burning (raw), using machines and green harvest. This strategy continued until the third ratoon harvest (4RH).

Table 2. Summary of the treatments at sampling. Numerals indicate the number of harvests that had taken place.

Cultivation Stages	Characterization
P-CH	The areas underwent conventional tillage, and after preparation, the planting of sugarcane was carried out using 12 tons of sugarcane stems per hectare (15/02/2018)
1RH	Experimental period after plant-cane harvest. The occurrence of one harvest (27/12/2018—unburned area, 16/01/2019—burned area)
2RH	Experimental period after the first crop. The occurrence of two harvests (28/12/2019—unburned area, 20/01/2020—burned area)
3RH	Experimental period second ratoon harvest. The occurrence of three harvests (15/12/2020—unburned area, 28/01/2021—burned area)
4RH	Experimental period after third ratoon harvest. The occurrence of four harvests (15/02/2022—unburned area, 20/02/2022—burned area)

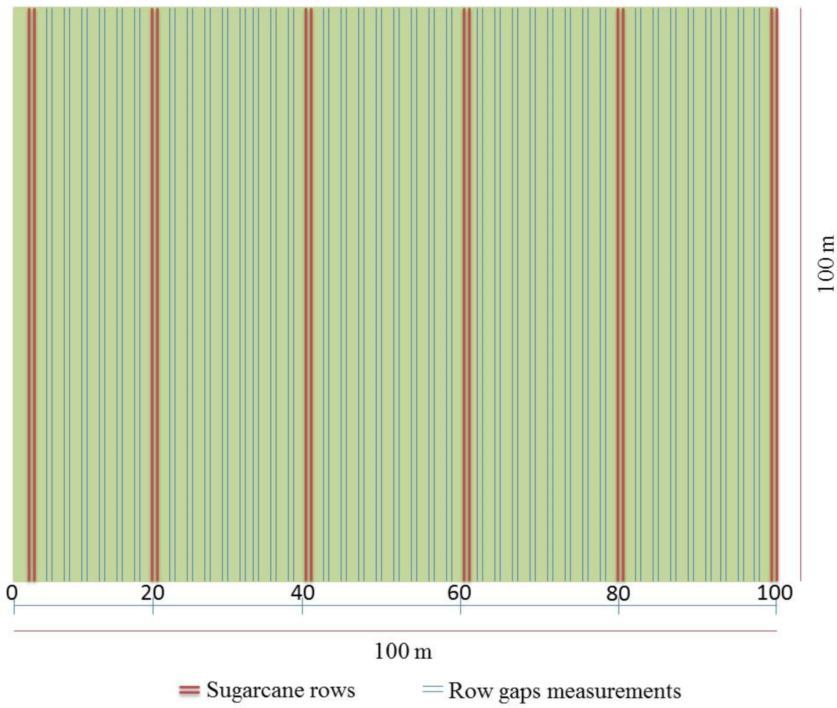


Figure 2. Rows used for the sugarcane row gaps measurement strategy used in the unburned and burned area.

For measuring row gaps, a tape measure was used to measure the distances between plants in each planting line with a length greater than 0.50 m [27]. The evaluation of gaps was performed approximately 90 days after each harvest stage of the sugarcane annual cycle.

The evaluation of row gaps was based on the following variables: the number of row gaps, where each gap in each row was counted individually; the gap length between rows (m), which was the sum of each gap length in each of the rows in each evaluated cultivation or harvest stage. Additionally, gaps were separated into five size classes (>0.5–1, >1–1.5, >1.5–2.0, >2.0–3.5, and >3.5 m) for an assessment of the predominance of gap size.

2.3. Statistical Analysis

The sugarcane row gaps number and length for the burned and unburned harvesting systems, as well as over the sugarcane annual stages, were evaluated using a 95% confidence interval for the means. The statistical procedures were performed in R software [28].

3. Results

3.1. Row Gap Number and Length

There was no difference between the burned and unburned management systems in terms of the row gap number and length (Figure 3). However, there was an increase in the number and length of row gaps over the annual sugarcane cultivation stage. The number of row gaps started at around zero for the P-CH cultivation stage, slightly increased at the 1RH stage (~5), and subtly increased after the 2RH stage (~40) in both sugarcane harvesting systems, reaching and averaging 60 row gaps.

When analyzing the average row gap number at the after sugarcane planting (P-CH) stage, there was little incidence of gaps, indicating that planting was effectively carried out in both areas, as the values were low, and it can be affirmed that the cultivation was homogeneous in both evaluated areas. It can also be inferred that the areas started the cycle in very similar conditions (Figure 3).

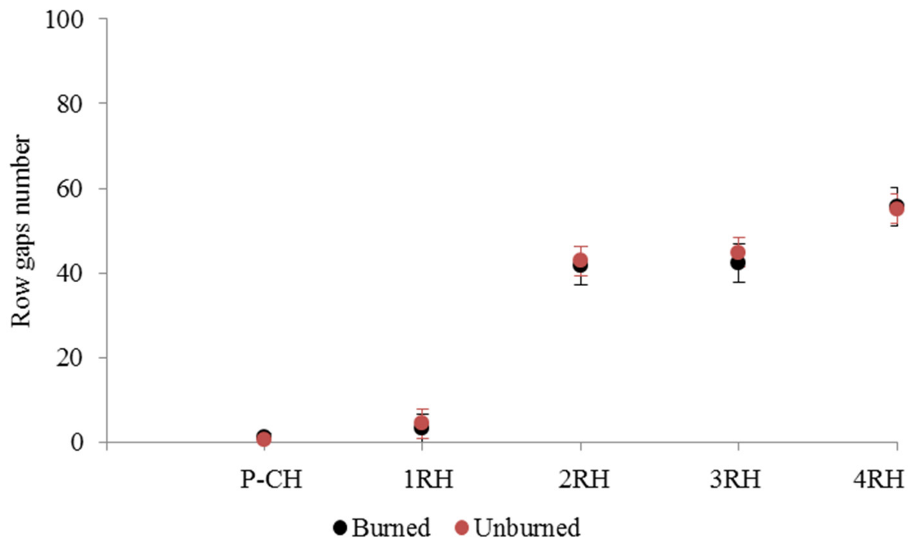


Figure 3. Sugarcane row gap number after sugarcane planting (P-CH), after the plant-cane harvest (1RH), after the first ratoon harvest (2RH), after the second ratoon harvest (3RH), and after the third ratoon harvest (4RH) in areas unburned and burned.

In 1RH, there was a slight increase in the average row gap number compared to the previous period, P-CH, thus showing no difference between these periods. It is important to note that during this transition, there was no machine traffic in either of the areas, as the harvested plants were used for seeds.

In 2RH, there was a significant increase in the average row gap number in both areas in relation to 1RH, i.e., 43 for the unburned area and 42 for the burned area. 3RH showed similar behavior to 2RH, with their values close together, indicating that there was no difference between the 2RH and 3RH cultivation stages. 4RH had the highest average row gap number (56 for the unburned area and 55 for the burned area), with them significantly differing from the other cultivation stages (P-CH, 1RH, 2RH, and 3RH).

Regarding the row gap length, there was a similar increasing trend in both harvesting systems' areas at all cultivation stages, indicating that there was no significant difference between burned and unburned harvests. P-CH and 1RH showed similar behavior (at P-CH, 0.8 m and 1.0 m for unburned and burned, respectively; at 1RH, 3.5 m and 4.0 m for unburned and burned, respectively), indicating no significant difference between these cultivation stages, as observed in the analysis of the average row gap number.

There was a significant increase in 2RH for the two areas (50.8 m and 41.8 m for unburned and burned, respectively) in relation to the previous cultivation stage, indicating a difference in comparison to the P-CH and 1RH cultivation stages. 3RH and 4RH showed similar behaviors, but it can be affirmed that the greatest extension of gaps was observed at 4RH (69.2 and 76.1 m for unburned and burned, respectively) and that the total row gap length in both areas was considerable throughout the harvests (Figure 4).

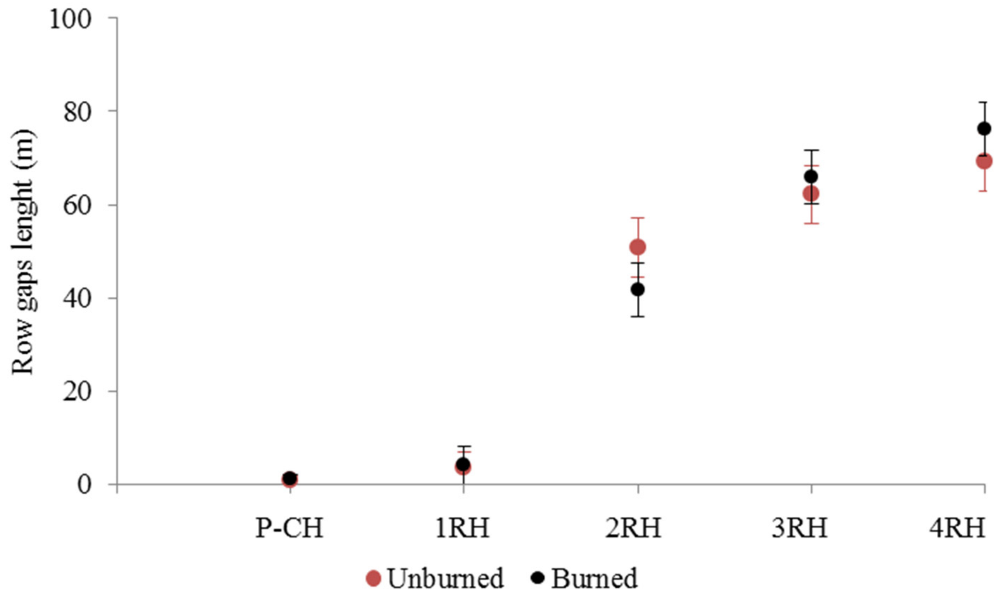


Figure 4. Row gap length (sum of gaps) for sugarcane after sugarcane planting (P-CH), after the plant-cane harvest (1RH), after the first ratoon harvest (2RH), after the second ratoon harvest (3RH), and after the third ratoon harvest (4RH) in areas unburned and burned.

3.2. Row Gap Number and Length Classes

Throughout the study period, row gaps belonging to the class between >0.5 and 1 m, followed by the class between >1 and 1.5 m, were predominant in both burned and unburned areas, indicating that most of the evaluated gaps fall within this class's range. Gaps with longer lengths (>3.5 m) were only observed from 2RH and continued to increase between 3RH and 4RH, indicating that in addition to increasing the row gap number over time, there was also an increase in the row gap length. Throughout the studied crop stages, the classes >1–1.5, >1.5–2.0, >2.0–3.5, and >3.5 m became more expressive in terms of the row gap number (Figure 5A,B), and this behavior was similar in both burned and unburned areas.

It is possible to observe that in P-CH, there were no major gaps present over 1.5 m, and only eight gaps were found in the class >0.5–1 m and five gaps in the class >1–1.5 m for the unburned area. For the burned area, this number was even lower within these two classes (Figure 5). For 1RH, there was a discrete increase in the row gap number and the presence of gaps in the classes >1.5–2 and >2–2.5 m for the unburned area, while the burned area continued to show the same behavior as the previous cultivation stage. Between the cultivation stages 2RH, 3RH, and 4RH, there was a considerable increase in the row gap number in all classes, especially in the class >0.5–1 m (Figure 5).

In general, the length/extension of gaps increased continuously throughout successive harvests (Figure 6). It can also be inferred that in P-CH and 1RH, the behavior was similar, meaning that in both periods, there were no gaps >3.5 m present, and only in the unburned area were there gaps in the classes >1.5–2 and >2–3.5 m, with a length of 8 and 5 m, respectively (Figure 6). From 2RH onwards, there was an increase in row gap length in all classes in both areas, and the unburned area showed higher values of row gap length in the classes >1.5–2, >2–3.5, and >3.5 (Figure 6).

In 3RH, the class >3.5 m showed a considerable increase in both areas evaluated, with 160 m for the unburned area and 166 m for the burned area (Figure 6), showing that gaps, in addition to increasing in number (Figure 5), also increased in length over the harvests. Similar behavior was observed in 4RH in the same area (Figure 6), but this last cultivation stage showed the greatest length of gaps in all classes and both areas. It is important to consider that the unburned and burned areas showed similar behavior regarding the row gap length per class.

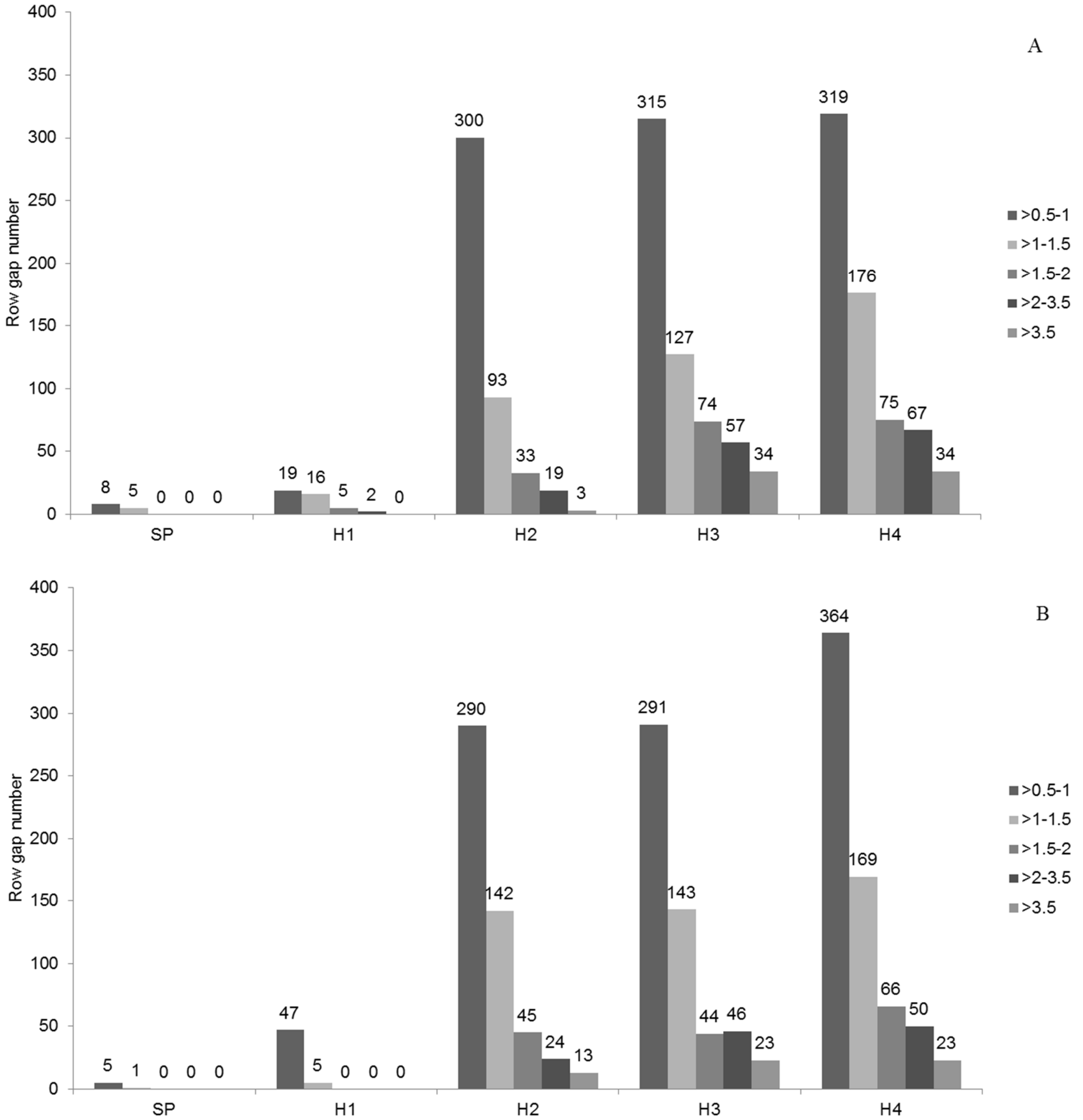
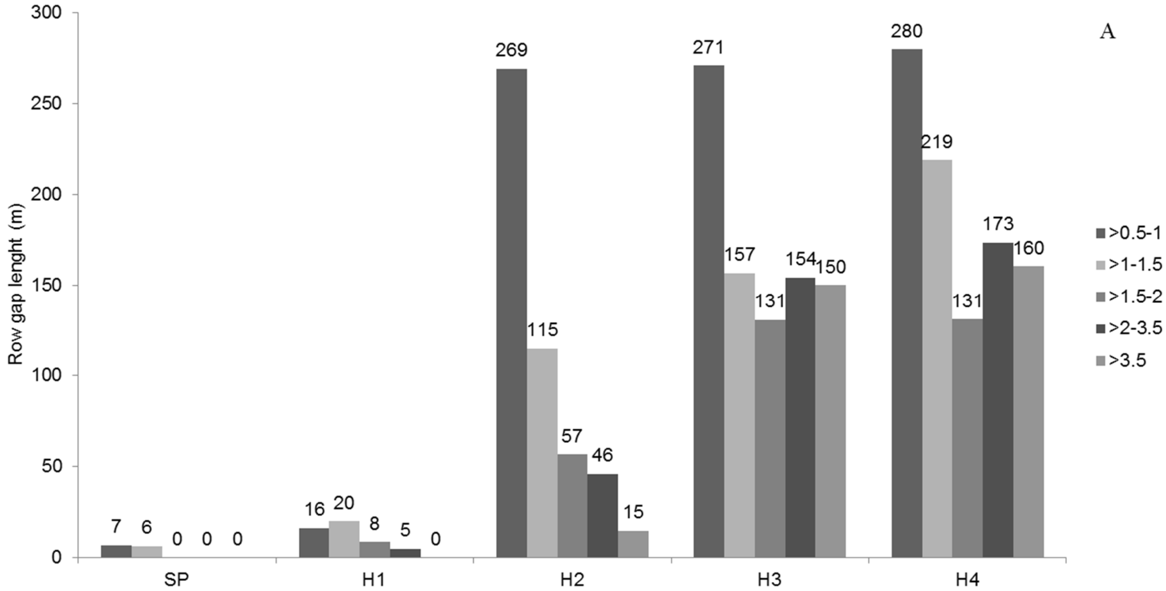


Figure 5. Row gap number per interval of classes >0.5–1, >1–1.5, >1.5–2.0, >2.0–3.5, and >3.5 m over successive sugarcane harvests: (**A**) unburned and (**B**) burned harvests after sugarcane planting (P-CH), after the plant-cane harvest (1RH), after the first ratoon harvest (2RH), after the second ratoon harvest (3RH), and after the third ratoon harvest (4RH).



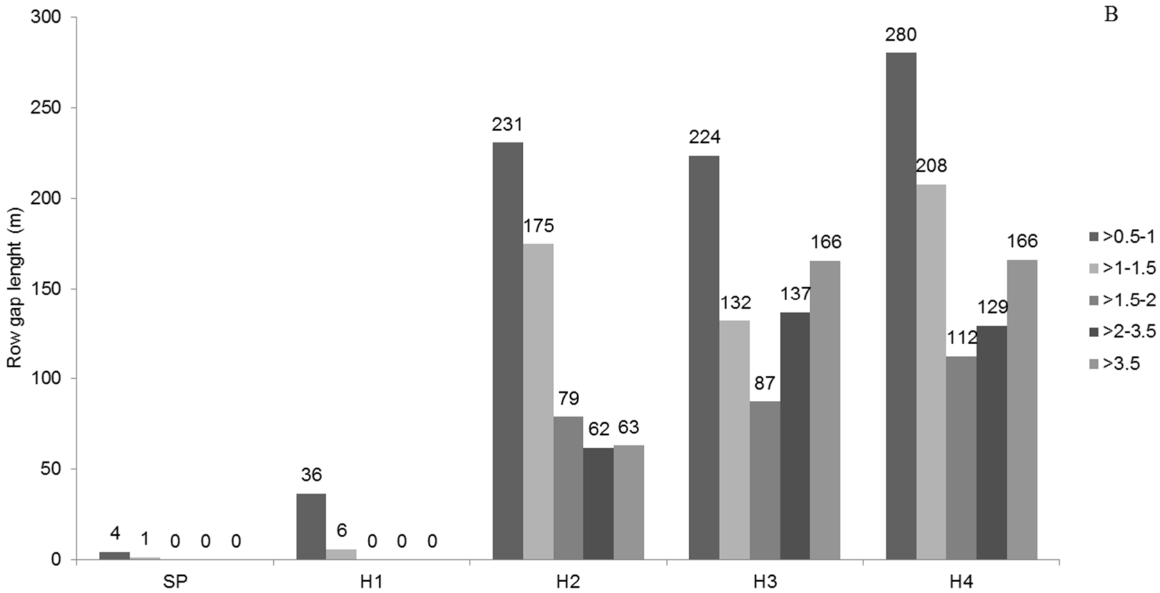


Figure 6. Row gap length per interval of classes, >0.5–1, >1–1.5, >1.5–2.0, >2.0–3.5, and >3.5 m over successive sugarcane harvests: (**A**) unburned and (**B**) burned harvests after sugarcane planting (P-CH), after the plant-cane harvest (1RH), after the first ratoon harvest (2RH), after the second ratoon harvest (3RH) and after the third ratoon harvest (4RH).

4. Discussion

4.1. Implications of Successive Sugarcane Harvests on the Emergence of Row Gaps

The row gap number and length were low in the P-CH and 1RH stages, indicating that soil preparation practices combined with the lack of traffic assisted in the initial plant development, which may be one of the causes of the reduced row gap number observed during this period. Supporting this statement, the authors of ref. [29] state that conventional soil preparation practices have been adopted as the main strategy to alleviate soil compaction prior to sugarcane planting. Soil preparation operations contributed to establishing ideal conditions for plant growth and crop development [29,30]. Therefore, sugarcane in the first year of development has the highest yield.

There is an increase in the row gap number throughout the production cycle because the effects of soil preparation are short-lived [31], and the soil returns to the same or worse state of compaction after one or two harvesting events due to high stresses applied by machine traffic [6,32,33].

Between 1RH and 2RH, the significant increase in row gaps may have been influenced by machinery operation, which caused plant damage due to tire and mechanical impacts. With the intensification of traffic during the harvests in both areas, the soil may have undergone a compaction process, reducing the porous spaces that are fundamental for crop development. According to ref. [34], the physical properties of the soil can be negatively affected after sugarcane harvests regardless of the system employed; they also state that successive harvests can increase the degree of compaction and considerably reduce the porous spaces of the soil, which consequently affects the plants and their ability to regrow, thus explaining the increase in the number of failures from 2RH.

Additionally, the authors of ref. [23] state that from the second harvest, phytosanitary factors and/or problems, such as inadequate management (trampling and uprooting), agricultural practices, or the occurrence of climatic conditions that can affect future yield (e.g., droughts or a decrease in photoperiod), can occur, and these situations can be analyzed through the presence of gaps in sugarcane planting, as they decrease production estimates.

In addition, it is important to consider mechanical damage caused by inadequate cutting due to machine operations, as they are responsible for promoting the entry of insects and fungi into the plant and affecting the ratoon to resprout [35]. The wear of the cutting blades can reduce the cutting quality of the stumps and the productivity of the stalks [5]. Damage to sugarcane stalks is associated with the impact of the cutting system. Therefore, inadequate cuts can negatively influence sprouting, with this being a possible cause for the increase in gaps over successive harvests [36].

4.2. Implications of Increasing Row Gap Number and Length Classes

The increase in the row gap number over the cycles is related to the damage caused to the sugarcane stools after cutting and even uprooting, making it difficult for them to regrow and consequently increasing the distance between plants with each new harvest. The authors of ref. [37] evaluated the performance of the harvester's cutting and observed that there was a greater presence of uprooted stalks after six harvests.

Similar findings were reported in ref. [11] regarding row gap length, where most of the evaluated areas tended to present a gap between 0 and 5 m. Additionally, newly planted areas showed smaller gaps when compared to the first year of harvest, and it is expected that the quantity and extension of gaps will increase every year. The percentage of gaps and the average size of gaps in sugarcane sprouting increase with the age of the plantation [13].

The main source of gaps in sugarcane plantations is the impact of machines directly on the plants and also on the soil, causing soil compaction and, consequently, mechanical damage to the plants, which, according to [38], can be one of the factors responsible for the reduction in sugarcane production. The authors of ref. [39] also state that gaps are a consequence of physical damage caused to the crop due to inadequate sugarcane harvesting and soil compaction.

The effect of traffic tends to be cumulative, as according to the results presented here, considerable differences were only noticed from the second to the last harvest, meaning that the effect of traffic on gaps seems to develop over time, which consequently negatively impacts crop yield. The authors of ref. [40] state that the quality of sugarcane cutting is of great importance, as any damage caused to the stalks and root system affects the ratoon and reduces productivity, leading to damage from the stalks to roots and even uprooting of the plant. The authors of ref. [41] consider that the characteristics of the plant variety combined with inadequate cutting can increase the number of damaged stalks and result in the loss of raw material.

The authors of ref. [24] assert that the decline in production is generally associated with an increase in row gap number and length in sugarcane plantations, which promotes a reduction in the number of plants. In line with these authors, the study presented here showed that the row gap number and extension were altered by the number of harvests, consequently reducing sugarcane production. There was a marked increase in gaps over time, but there was no difference between the burned and unburned management systems, which may have occurred due to the cutting and management systems employed and also due to soil compaction caused by random agricultural machinery traffic.

5. Conclusions

Our results suggest that row gaps in the sugarcane field are independent of the burned or unburned sugarcane harvesting system. However, the number of row gaps in both harvesting systems increases with the number of harvests. From the crop year, the number of row gaps seems to stabilize. Regarding the classification of gaps, it was possible to notice a predominance of row gaps in the range between >0.5 and 1.5 m in both management systems and over all harvest stages.

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