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Sugarcane canopy influence on the performance of mechanized sprinkler irrigation systems

Influencia del dosel de la caña de azúcar en el desempeño del sistema de riego por aspersión mecanizada

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ABSTRACT

Sugarcane cultivation is one of the most significant agro-industrial sectors, substantially contributing to the country's agricultural Gross Domestic Product (GDP). Under local conditions, surface irrigation is applied to 90% of the crop, achieving efficiency rates of no more than 50%. Therefore, one of the irrigation systems being implemented to improve application and distribution efficiency, as well as water resource management, is the traveling-cannon mechanized sprinkler system. The objective of this study was to assess the impact of the sugarcane canopy on water distribution uniformity and its subsequent effect on water application efficiency. To achieve this, the Christiansen Uniformity Coefficient (CUC), the Coefficient of Statistical Uniformity (CSU), and the Coefficient of Uniformity of Distribution (CUD) were used to evaluate equipment performance in accordance with the ASABE S436.1 standard for field data collection. The trials were conducted at three phenological stages of the crop: 0–3 months, when the plant canopy does not interfere with the distribution of applied water; 3–6 months, when the crop canopy is not expected to significantly affect water distribution; and 6–9 months, when the crop canopy begins to interfere with distribution uniformity. The results showed that irrigation at the 6–9-month stage negatively affected distribution uniformity, with a 40% reduction in uniformity observed under non-overlapping equipment conditions.

Keywords: Christiansen Uniformity Coefficient; evaluation; phenological stage; simulation; uniformity; water distribution uniformity

RESUMEN

El cultivo de caña de azúcar es uno de los sectores agroindustriales más importantes en términos de su contribución al producto interno bruto (PIB) agrícola del país. Bajo condiciones locales, se aplica riego superficial al 90% del cultivo, logrando tasas de eficiencia de no más del 50%. Por lo tanto, uno de los sistemas de riego que se está implementando para mejorar la eficiencia de aplicación y distribución, así como la gestión de los recursos hídricos, es el sistema de aspersión mecanizada de cañón viajero. El objetivo de este estudio fue evaluar el impacto del dosel de la caña de azúcar en la uniformidad de la distribución del agua y su efecto posterior en la eficiencia de aplicación del agua. Se emplearon el Coeficiente de Uniformidad de Christiansen (CUC), el Coeficiente de Uniformidad Estadístico (CUE) y el Coeficiente de Uniformidad de Distribución (CUD) para evaluar el rendimiento del equipo, de acuerdo con los estándares ASABE S436.1 para la recopilación de datos de campo. Los ensayos se realizaron en tres etapas fenológicas del cultivo: 0-3 meses, durante los cuales el dosel de la planta no interfiere con la distribución del agua aplicada; 3-6 meses, cuando se estima que el dosel del cultivo no afecta significativamente la distribución del agua; y 6-9 meses, cuando la cubierta vegetal comienza a interferir con la uniformidad de la distribución. Los resultados mostraron que el riego entre los 6 y los 9 meses afectó negativamente la uniformidad de la distribución, con una reducción del 40 % en la uniformidad observada en condiciones de equipos sin solapamiento.

Palabras clave: Coeficiente de Uniformidad de Christiansen; eficiencia del agua; etapa fenológica; simulación; uniformidad; uniformidad de distribución del agua

INTRODUCTION

Sugarcane cultivation in Colombia is a key agro-industrial sector in the national economy, accounting for 0.6% of total GDP and 2.5% of agricultural GDP. In Valle del Cauca, it accounts for 21.1% of agricultural GDP and 11.1% of industrial GDP, while in Cauca, it accounts for 11.9% of agricultural GDP and 21.4% of industrial GDP (ASOCAÑA, 2024).

Traveling sprinkler irrigation consists of a two-part system: a vehicle-mounted sprinkler and a reel connected to a water source. The sprinkler moves in a straight line while irrigating, powered by a polyethylene hose connected to the reel. This hose has a highly efficient turbine that uses 10% of the supplied pressure to propel the sprinkler. Once irrigation is complete and the hose is fully coiled, the system can be rotated 180° to repeat the process, enabling the irrigation of two distinct areas (Tarjuelo Martín-Benito, 1991).

Crop yield, along with other outcomes, is significantly influenced by irrigation uniformity, which is regarded as a critical factor in the proper functioning of irrigation systems (Bernardo *et al.*, 2009). Uneven water distribution results in areas experiencing water deficits as well as areas with excess moisture. However, achieving greater uniformity in water application incurs higher costs, primarily related to system operation and maintenance (Mendoza *et al.*, 2020a).

The uniformity of water distribution in sprinkler systems is influenced by both climatic factors (such as evaporation, air temperature, relative humidity, and wind) and equipment-related non-climatic factors, including sprinkler type, operating pressure, distance, travel speed, lateral line alignment, and emitter height (Heinemann *et al.*, 1998; Li & Kawano, 1996; Mendoza *et al.*, 2020b).

Therefore, performance parameters such as water application uniformity are essential for assessing irrigation quality. Several coefficients have been developed to quantify this uniformity (Frizzone & Dourado Neto, 2003).

MATERIALS AND METHODS

The tests were conducted at the Florencia farm in the department of Valle del Cauca, at coordinates 03° 18’ 1.623” N, 76° 22’ 49.3134” W, at an altitude of 974 meters above sea level. The climate in the area is warm and dry, with an average annual temperature of 23 °C and average annual rainfall of 1221 mm. The tests were performed in the morning to minimize the impact of wind on the uniformity of water distribution by the traveling gun (TG) equipment.

According to Cenicaña (2021), the three crop age ranges used to evaluate canopy interference with the distribution of water reaching the soil, as applied by the mechanized sprinkler system, were based on the agronomic and vegetative characteristics of the sugarcane planted in the experimental area, as well as on the largest area planted that year. The evaluation was carried out using the CC01-1940 variety, which accounted for an estimated 42.22% of the total area planted that year. Based on these factors, the following age ranges were selected: 0–3 months, during which the cane canopy has not yet interfered with water distribution or covered the rows or inter-row spaces; 3–6 months, when the canopy may begin to interfere with water distribution as it starts to cover the inter-row spaces; and 6–9 months, when the canopy reaches its maximum growth and causes the greatest interference with water distribution, completely covering the inter-row spaces. Beyond this age, irrigation using the equipment is no longer feasible, as the crop canopy fully obstructs field traffic.

The equipment used was an Irrimec-brand traveling cannon, model Master MF1/3B series. It features a hydraulic system that connects to the tractor's hydraulic system. Key specifications include a 350-m hose, an operating pressure of 60–70 psi for the cannon, a reel pressure of 95–102 psi, and a water application range of 20–70 mm.

The evaluation configuration followed the procedure outlined in the ASAE S436.1 standard, "Test Procedure for Determining the Uniformity of Water Distribution of Center Pivot and Lateral Move Irrigation Machines Equipped with Spray or Sprinkler Nozzles" (ASABE, 2020). Three lines of yellow cylindrical rain gauges, each with a diameter of 8 mm, a height of 7 cm, and a volume of 3.5 cm^3, were arranged to collect the precipitation applied by the equipment. These evaluation lines were spaced uniformly 5 m apart and positioned perpendicular to the direction of travel of the traveling cannon. The height from the ground to the collector was 0.6 m, and the distance between collectors along each line was 1.65 m. This spacing corresponds to the spacing between furrows in the crop, so the collectors were placed in the inter-row spaces, where irrigation water is typically applied in both surface and sprinkler irrigation systems.

To determine the conditions under which the traveling cannon irrigation equipment distributed water, different performance coefficients were used to classify water distribution and assess the canopy's interference with this distribution. Therefore, the Christiansen uniformity coefficient (CUC) was used (Christiansen, 1942). It is a statistical measure of uniformity defined as the absolute deviation of individual precipitation observations from the mean, divided by the average precipitation collected (Equation 1). The coefficient of statistical uniformity (CSU), determined by Wilcox and Swailes in 1947 and defined as a statistical parameter involving the standard deviation and mean of the collected precipitation (De Andrade *et al.*, 2021) (Equation 2), was also used. The coefficient of uniformity of distribution (CUD), defined by Merrian and Keller in 1978, considers the average precipitation collected in the 25% of the least irrigated area relative to the total average collected (Montero Martínez, 1999) (Equation 3).

$$CUC = 100\left(1 - \frac{\sum_{i=1}^{n}|X_i - \bar{X}|}{n * \bar{X}}\right) \qquad \text{Equation 1}$$

$$CSU = 100\left(1 - \frac{S}{\bar{X}}\right) \qquad \text{Equation 2}$$

$$CUD = 100\left(\frac{X_{25\%}}{\bar{X}}\right) \qquad \text{Equation 3}$$

Where:

X_i: Depth of water collected at rain gauges "i", mm

n: Number of rain gauges

$\bar{X}$: Average depth of water collected by the rain gauges, mm

S: Standard deviation of the water depth data

$X_{25\%}$: Average depth of water collected by the lowest 25% of the rain gauges, mm

Similarly, to irrigation quality using these parameters, a classification system (Table 1) is employed to determine the performance of the operation in qualitative terms.

Table 1. *Classification of water distribution uniformity coefficients*

Classification	CUC	CUD	CSU
		%	
Excellent	> 90	> 84	90 – 100
Good	80 – 90	68 – 84	80 – 90
Reasonable	70 – 80	52 – 68	70 – 80
Poor	60 – 70	36 – 52	60 – 70
Inadequate	< 60	< 36	< 60

Source. Mantovani (2001), adapted.

The different evaluations were conducted at the same time of day, during the early morning hours, to minimize wind interference with water distribution, as wind is one of the most significant factors affecting sprinkler irrigation. Wind speed and direction were also monitored using a Davis anemometer connected to a Vantage Pro 2.0 station, located 2 m above the ground surface and within a 200-m radius of the assessment site. Data were recorded at 15-minute intervals throughout the assessment.

RESULTS

For the trials conducted at each crop age, the selected and programmed operating speed of the equipment was 24 m/h, corresponding to an applied irrigation depth (ID) of 41 mm, which was the depth used by the production unit based on soil and crop conditions. The design used to collect water distribution data with the traveling gun is shown in Figure 1, which illustrates the three rainfall collection lines used to evaluate the irrigation equipment. This setup includes three replicates for each distribution evaluation, as well as two additional locations spaced 30 m apart, providing an additional set of complete replicates under the same operating and evaluation conditions.

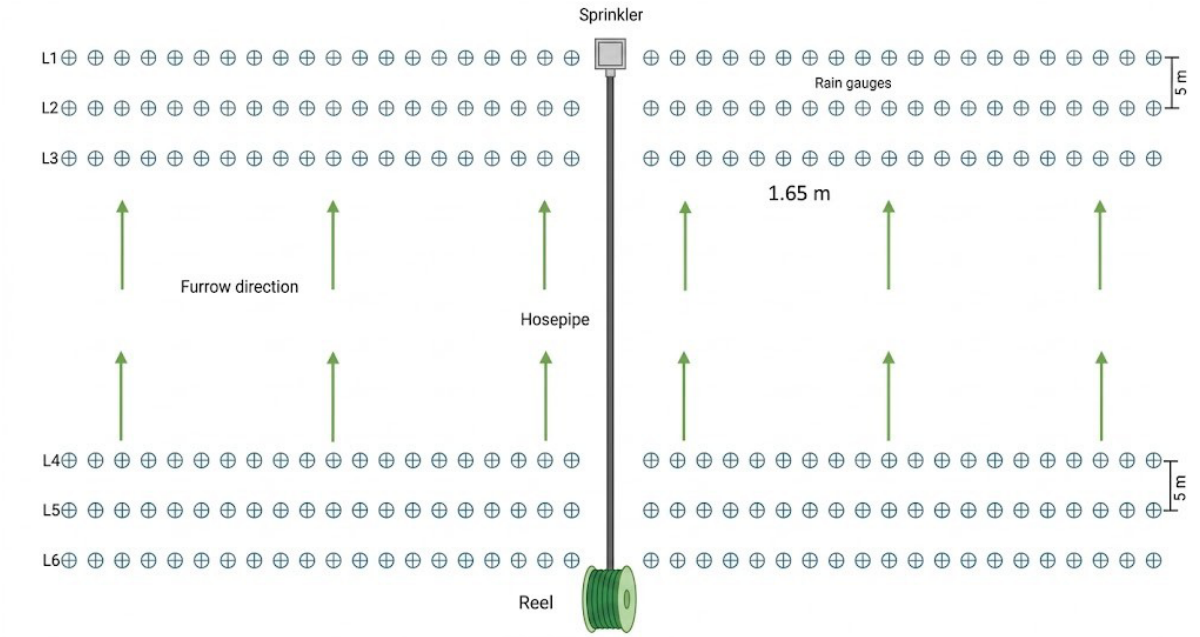

Figure 1. *Experimental design with furrow direction parallel to the movement of the traveling gun*

As an initial assessment, the water distribution provided by the TG equipment (Figure 2a) was evaluated at 0–3 months of crop age, indicating no canopy interference with water application.

Based on the data collected during the evaluation, the optimal overlap for the irrigation equipment was determined, specifically the spacing at which the equipment should operate along the lateral irrigation lines. Figures 2b–2f show the profiles for each simulated overlap.

As shown in Figure 2a, the distribution profile of the traveling cannon equipment exhibits the characteristic pattern of a sprinkler operating in isolation, as described by Keller and Bliesner (2001), with an elliptical distribution based on the average of all collected rainfall lines. A second-degree polynomial trend line fitted to the data yielded an R^2 of 0.956. Additionally, this analysis indicates that the optimal overlap for maximizing the uniformity coefficient was 40%, as shown in Figure 2e, where the trend line of the precipitation data forms a straight line with values close to the programmed irrigation depth (ID).

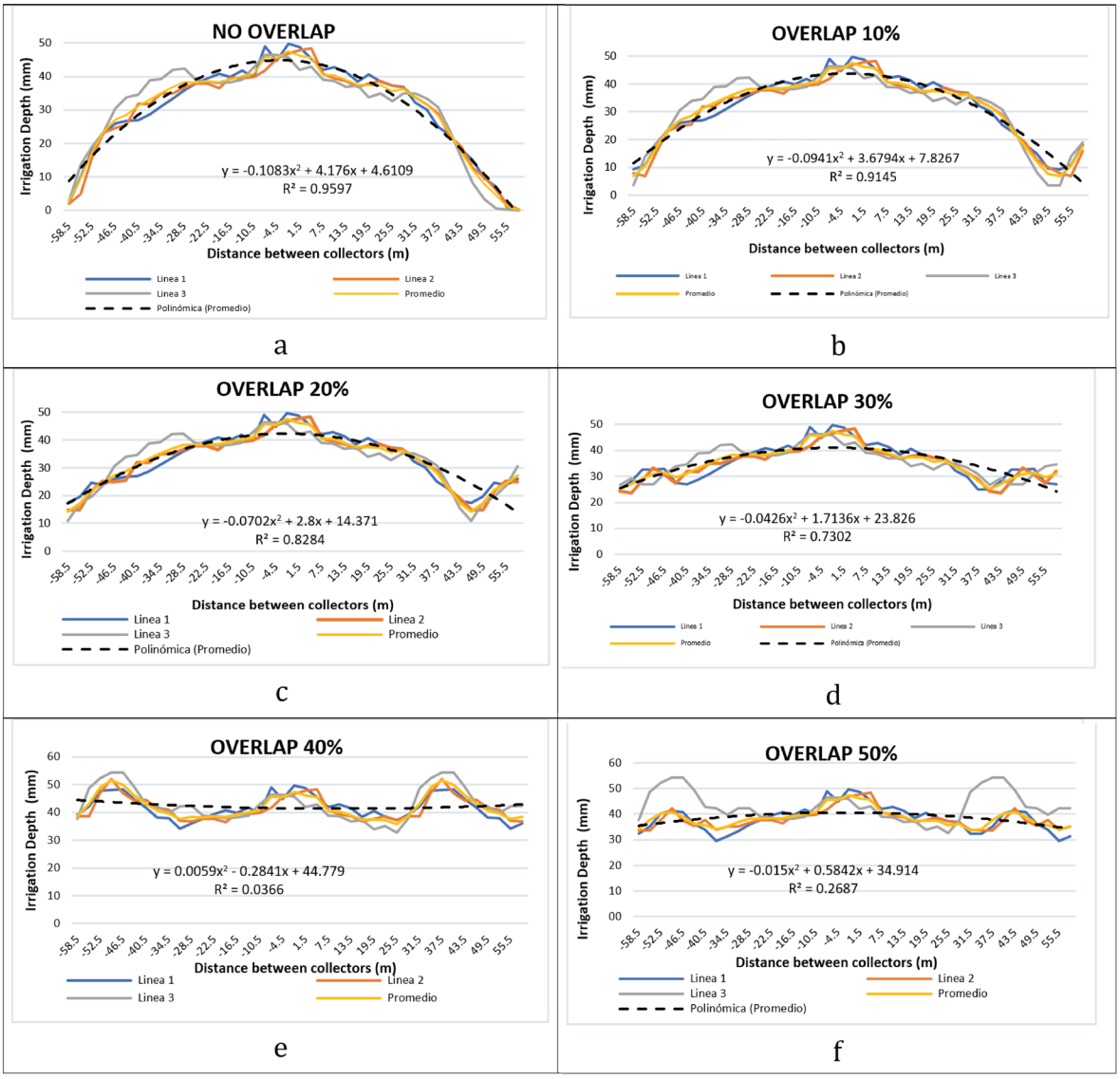

Figure 2. *Distribution profile (a) and simulated overlaps (b-f) used to determine water distribution and applied depth for the 0–3-month crop age*

To achieve the programmed irrigation depth of 41 mm, a 40% or 50% overlap between the irrigation lines and the equipment should be used, given the equipment's travel speed. This is illustrated in Table 2, which shows how the selected overlap directly affects the uniformity coefficient (UC). Furthermore, while higher overlaps do not necessarily improve water distribution uniformity, they result in greater irrigation depths, potentially exceeding the programmed depth. This, in turn, could lead to higher irrigation costs.

Table 2. *Irrigation quality indicators for different overlaps at the 0–3-month crop age*

Overlap (%)	ID (mm)	CUC	CUD	CSU
			%	
0	30.3	62.8	31.2	54.5
10	31.1	67.5	41.6	60.9
20	32.9	75.6	59.4	71.0
30	35.4	85.0	76.8	82.0
40	38.6	91.6	87.1	89.1
50	42.2	90.3	87.2	88.1

Therefore, the overlaps could achieve an irrigation depth determined by the equipment's travel speed (41 mm). This would be the case for a 40% overlap, which results in an irrigation depth of 38.6 mm, a 5.9% reduction, or 2.4 mm less than the programmed depth. Similarly, for the 50% overlap, the irrigation depth would increase by 2.3%, with an ID 1.2 mm higher than the programmed depth.

However, this decision must consider, among other factors, the quality of the irrigation work. The highest uniformity coefficient (UC) is achieved with 40% and 50% overlap, reaching 91.6% and 90.3%, respectively. Additionally, increasing the spacing between irrigation lines reduces distribution uniformity, which leads to a decrease in irrigation depth. Even with a 30% overlap, the ID decreases by 13.7%, resulting in a 5.6 mm reduction, which accounts for crop evapotranspiration over a two-day period.

Moreover, when evaluating the irrigation distribution performance of the traveling cannon using the coefficient of uniformity of distribution (CUD), the values for 40% and 50% overlap are very similar, around 87%. If this performance parameter is used, it would allow for greater spacing between irrigation lines and lower operational costs. On the other hand, when using the coefficient of statistical uniformity as the performance parameter, the highest value is observed with the 40% overlap, with a CSU of 89.1%. For the 50% overlap, there is a slight decrease in CSU, resulting in a value of 88.1%.

Based on the comparison of the three performance parameters evaluated, as shown in Table 1, only the 40% and 50% overlaps for CUC and CUD are classified as excellent. However, when using the CSU as the performance parameter, none of the simulated overlaps are classified as excellent. Even with 40% and 50% overlaps, the classification drops to good.

Continuing the analysis of canopy interference on water distribution, the crop was evaluated at 3–6 months of age. Under the same operating conditions, including irrigation equipment, travel speed, and evaluation schedule, it was determined that the crop canopy interfered with application uniformity. This was confirmed for the same overlaps defined previously, as shown in Figure 3.

Although the distribution profile of the equipment operating in isolation remains elliptical, as observed in the first test without crop canopy interference, changes in the rainfall lines are also evident. This is reflected in the R^2 value for the same second-degree polynomial trend equation, which is lower than that of the initial test, with a value of 0.92.

From the water distribution profiles (Figures 3b–3f), it is evident that, in most cases, the irrigation depth determined for the task cannot be applied. This indicates interference from the crop canopy with the water distribution delivered by the traveling cannon equipment. However, this does not mean that the total amount of water applied is reduced; rather, canopy interference decreases the amount of water applied to the same area, and some of this water may be retained by the canopy without effectively reaching the root zone.

From Figure 3f, with a 50% overlap, it can be determined that this irrigation configuration has a low irrigation depth, with the highest value approximately 31 mm, and a more linear water distribution profile, which is recommended when overlapping irrigation to make the applied depth uniform throughout the irrigated area.

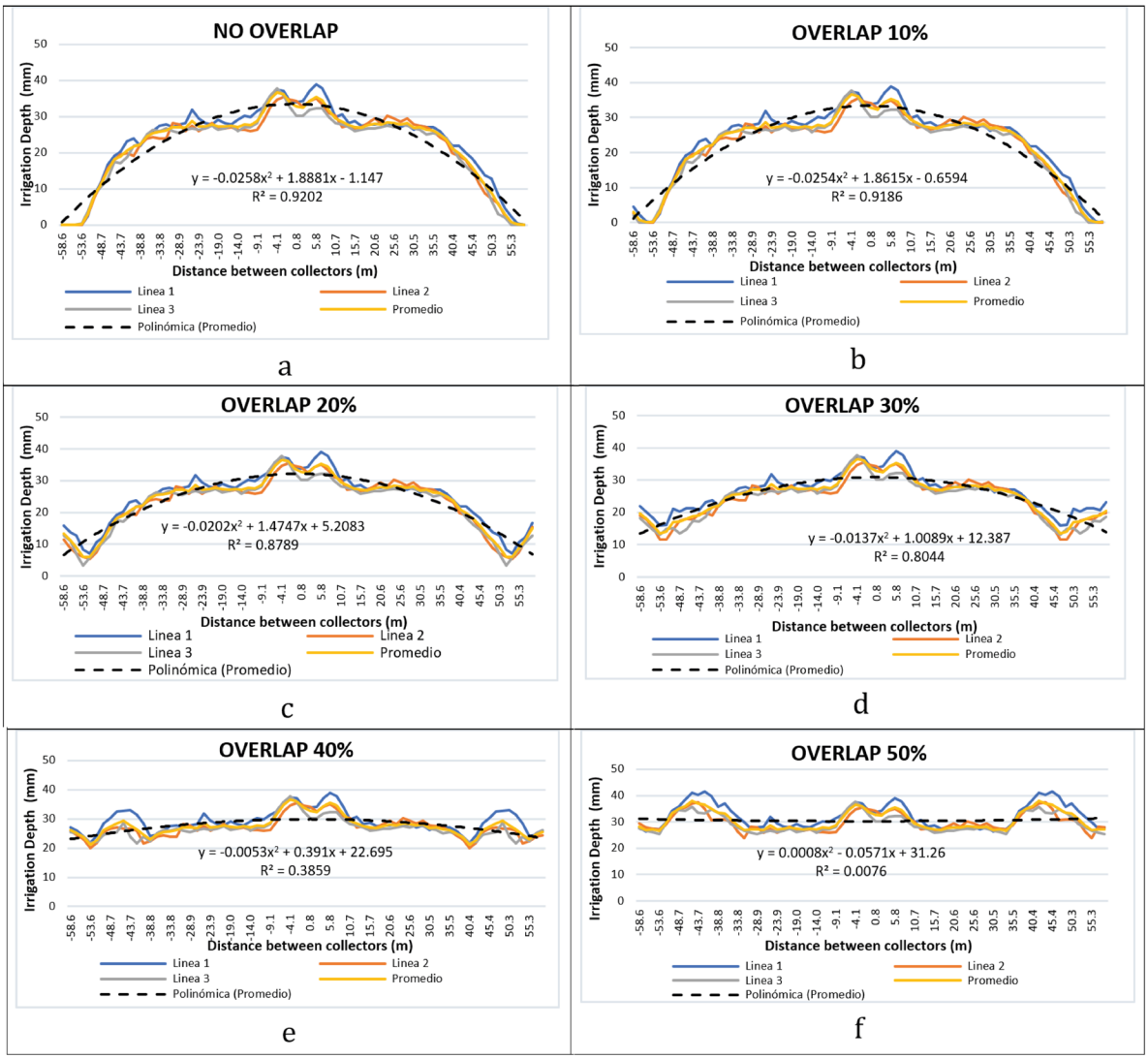

Figure 3. *Distribution profile (a) and simulated overlaps (b-f) to determine the water distribution and applied depth for the 3–6 months crop age*

Thus, when determining the values of the performance parameters (Table 3), a decrease in irrigation depth is observed. On average, for the largest overlap (50%), there is a reduction of 10.4 mm of water, representing a 25.4% decrease in the programmed ID for the task. This can be even more critical if the water balance is based on the full 41 mm, when only 31 mm is being applied, potentially leaving the crop under water stress for several days.

Table 3. *Irrigation quality indicators for different overlaps at the 3–6 months crop age*

Overlap (%)	ID (mm)	CUC	CUD	CSU
		%		
0	22.3	62.4	28.2	53.1
10	22.4	62.9	29.2	53.7
20	23.5	70.5	46.0	64.0
30	25.0	80.1	66.1	75.5
40	27.6	89.8	84.9	86.5
50	30.6	88.5	86.2	83.0

The performance indicator values also show a decrease, reflecting interference from the plant canopy with the water distribution provided by the equipment. These values show decreases of 5.1% for the CUC at a 20% overlap, 13.4% for the CUD at the same overlap, and 7.2% for the CSU at a 10% overlap. This suggests that if the performance indicator is the CSU, overlaps below 20% would result in irrigation quality being considered unacceptable, as they would fail to provide adequate uniformity to meet the crop's water requirements. Therefore, for the CUC—widely used to assess irrigation performance at this stage and in the presence of the canopy's interference—overlaps below 20% would be classified as unacceptable, thus compromising the ability to meet the crop's water needs effectively.

During the 6–9-month crop stage, when the plant canopy causes the greatest interference with the sprinkler's water distribution, it can be observed (Figure 4a) that, although the equipment's distribution profile in isolation remains elliptical, as shown earlier (Figure 2a), there is a noticeable decrease in uniformity across the rain gauges relative to the collected depth. This decrease is primarily caused by the crop canopy's interference. Additionally, the R^2 value decreases to 0.297, indicating a low correlation between the collected precipitation data and the elliptical distribution profile observed for the sprinkler operating in isolation, where the R^2 was 0.956.

Likewise, the interference caused by the canopy with the water distribution reaching the ground is evident. This interference results in some water application points recording depths greater than 50 mm, while others register zero. Additionally, across all repetitions or rainfall collection lines, the interference pattern remains consistent, indicating the uniformity of the interference caused by the canopy.

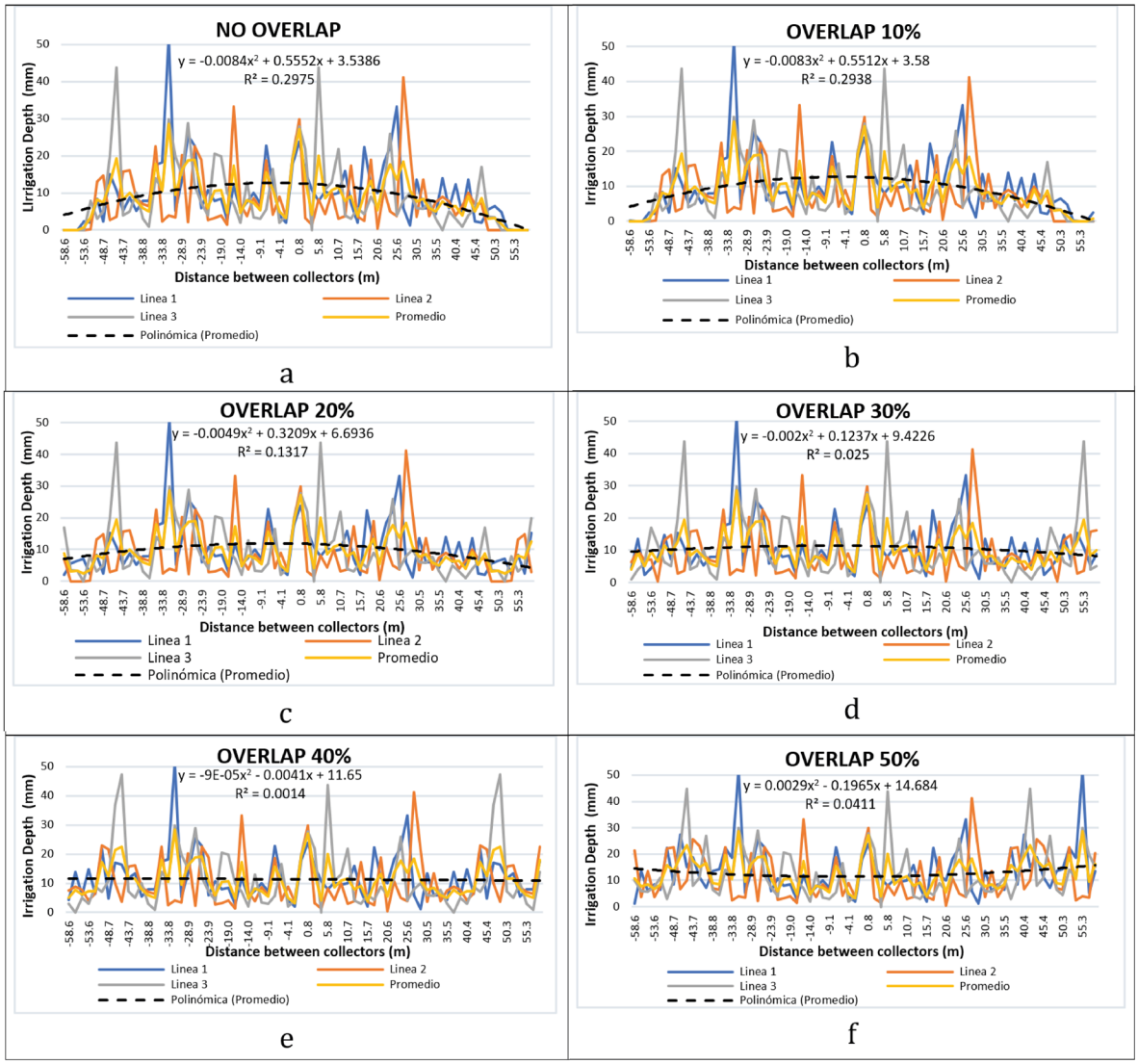

Figure 4. *Distribution profile (a) and simulated overlaps (b-f) for determining the water distribution and applied depth for the 6 – 9 months crop age*

When the rainfall data are evaluated using the different irrigation performance indicators (Table 4), a significant decrease is observed across all indicators, leading to the classification of the irrigation work as unacceptable according to Table 1. This aligns with the findings of Mesquita da Silva *et al.* (2021), who evaluated the same crop, sugarcane, at two different heights and found that crops at greater heights interfered with water distribution, with the impact more pronounced at larger sprinkler spacings. Similar results were reported by Ayars *et al.* (1991), who assessed the interference of cotton crops with water distribution by sprinkler systems and found that smaller irrigation depths led to greater interference in the CUC.

Table 4. *Irrigation quality indicators for different overlaps at 6 – 9 months of crop age*

Overlap (%)	ID (mm)	CUC	CUD	CSU
			%	
0	9.03	25.3	10.3	0.2
10	9.04	25.5	10.8	0.4
20	9.71	32.6	20.3	10.0
30	10.5	37.5	25.9	16.1
40	11.3	37.9	25.7	17.8
50	12.7	40.1	26.0	23.8

Among the performance indicators, the highest CUC is observed in the 0–3-month age group, with a 40% overlap of 91.6%. In the 6–9-month age group, the CUC at the same overlap is only 37.9%, representing a decrease of 53.7 percentage points, the largest drop in CUC performance. These decreases are even more pronounced in the CUD and CSU, with reductions of 61.4 and 71.3 percentage points, respectively.

The results for the collected water depth in the 6–9-month age group (Table 3) demonstrate a decrease in the applied water, which does not indicate a "loss" of water but rather an uneven distribution. Part of this water will still reach the soil via the sugarcane canopy. Additionally, the decrease in the collected layer, with the highest simulated value occurring at a 50% overlap, shows a reduction of 28 mm in the applied water. This could represent the amount of water that does not reach the soil, instead remaining in the canopy due to its high interference, where it will subsequently evaporate.

Therefore, based on the latest trials, it could be concluded that conducting evaluations with collectors placed above the canopy could represent the water application by the irrigation system without interference from the crop. However, Zapata *et al.* (2018) demonstrated that placing collectors above the canopy for tall plants, such as sugarcane, would affect the results of the system's performance evaluation.

DISCUSSION

The results of this study clearly demonstrate that the performance of the traveling gun irrigation system is strongly affected by the structural development of the sugarcane canopy. During the early crop stage (0–3 months), when canopy interference is minimal, the system maintains an elliptical distribution pattern typical of sprinklers operating in isolation. Under these conditions, 40% and 50% overlap yield the highest uniformity coefficients (CUC, CUD, and CSU), with 40% providing the most efficient balance between irrigation depth and water distribution uniformity. These findings are consistent with previous studies showing that the performance of traveling gun irrigation systems is strongly dependent on the spatial overlap of sprinkler application patterns, travel-lane spacing, and operating conditions (Shull & Dylla, 1976; Prado & Colombo, 2020).

As the crop advances to the 3–6-month stage, the developing canopy significantly alters the distribution pattern, reducing both uniformity and the effective irrigation depth. Although higher overlaps still achieve acceptable uniformity, the applied depth decreases by more than 20% in some cases, confirming that a considerable portion of the applied water is intercepted by the canopy rather than reaching the soil. Similar

interactions among canopy development, plant morphology, and sprinkler water interception have been documented in tall crops, with interception varying by growth stage, plant architecture, and irrigation characteristics (Zhu *et al.*, 2023). The behavior observed in the present study is also consistent with findings from sugarcane irrigation under center pivot systems, where differences between the uniformity of water applied at the soil surface and the subsequent distribution of soil water were observed (Mendoza *et al.*, 2020a). These results highlight the importance of considering canopy development when evaluating irrigation performance, since high surface application uniformity does not necessarily translate into an equivalent distribution of water within the soil profile.

During the 6–9-month stage, the canopy reaches its maximum density and height, producing the most severe interference. The distribution pattern becomes highly irregular, the polynomial fit deteriorates drastically (R^2 = 0.297), and all performance indicators fall into the "unacceptable" classification. The system fails to deliver the programmed irrigation depth, with deficits up to 28 mm, even at the highest overlap level. Spatial variability is extreme, with some points receiving over 50 mm and others none, indicating strong obstruction and redirection of water by the canopy. Previous studies have shown that dense canopies in tall crops can substantially alter sprinkler water distribution and irrigation uniformity below the canopy, with these effects influenced by crop development, operating pressure, nozzle characteristics, and droplet size (Zapata *et al.*, 2018; Hui *et al.*, 2021; Wang *et al.*, 2023). In sugarcane, Teixeira *et al.* (2012) demonstrated that water interception by the canopy increased markedly with leaf area index, reaching approximately 32% at a leaf area index of 3.5, highlighting the important role of crop architecture in modifying the amount and distribution of water reaching the soil. The pronounced decline in uniformity observed in the present study, reaching 71 percentage points in CSU, is therefore consistent with the strong influence that crop architecture can exert on sprinkler water redistribution.

The comparison of the three crop stages shows that overlap adjustments can partially compensate for distribution variability in younger crops but are insufficient once the canopy becomes dense. Furthermore, increasing overlap raises operational costs by increasing water application without improving the water that actually reaches the root zone, indicating diminishing returns under dense-canopy conditions. This limitation is particularly relevant for traveling gun systems operating in tall, mature crops, where canopy interception can substantially alter water redistribution within the crop (Prado & Colombo, 2020; Teixeira *et al.*, 2012). Furthermore, the stage-dependent water requirements of sugarcane underscore the importance of adapting irrigation management to crop development rather than relying solely on adjustments in sprinkler overlap (Gurski *et al.*, 2020).

Finally, the results confirm that evaluation methods play a crucial role in accurately assessing irrigation performance. As noted by Zapata *et al.* (2018) and reinforced by Mendoza *et al.* (2020a), placing collectors above the canopy can lead to misleading conclusions because it neglects interception and redistribution within the foliage. Therefore, ground-level measurements are essential for determining the actual irrigation depth delivered to the root zone.

Overall, this study shows that the traveling gun irrigation system performs adequately only during the early stages of sugarcane growth. As the crop develops, canopy interference significantly reduces both uniformity and effective irrigation depth. These findings underscore the need for stage-dependent operational strategies and a reconsideration of this technology for mature sugarcane, where alternative irrigation systems may offer superior performance.

CONCLUSIONS

The sugarcane canopy significantly reduces water distribution uniformity, especially as the crop matures. The greatest interference occurs during the 6–9-month stage, when the canopy reaches full development and degrades the performance of the traveling gun irrigation system. At the early crop stage (0–3 months), minimal canopy interference allows for higher irrigation uniformity. Overlaps of 40% and 50% are optimal for achieving the highest uniformity coefficients (CUC and CSU), with 40% being the most efficient in balancing water distribution and operational costs. For the later stages (3–6 months and 6–9 months), the effectiveness of these overlaps declines due to increased canopy interference, leading to lower uniformity. Canopy interference reduces the applied irrigation depth and creates uneven water distribution. While the total water applied does not necessarily decrease, a portion is retained by the canopy, preventing it from reaching the root zone efficiently. This can lead to periods of water deficit in the crop, particularly during the more mature stages. The irrigation quality indicators (CUC, CSU, and CUD) show a significant decline as the crop matures. For the 6–9-month stage, all overlaps (except the lowest) were classified as “unacceptable” in terms of irrigation performance. This is particularly evident in the CUC, which decreased by 53.7% at 40% overlap, indicating that the crop canopy’s effect on water distribution is most critical during the mature stages of growth. While higher overlaps (40% and 50%) improve irrigation uniformity, they also increase water application, raising operational costs. Therefore, careful consideration is needed to balance uniformity with irrigation depth to optimize costs without compromising crop water requirements.

AUTHOR CONTRIBUTIONS

Conceptualization, C.J.M.C.; Methodology, C.J.M.C.; Validation, C.J.M.C.; Resources, C.J.M.C.; Supervision, C.J.M.C.; Formal Analysis, C.J.M.C.; Funding Acquisition, C.J.M.C.; Project Administration, C.J.M.C.; Software, D.V.D.N. and C.J.M.C.; Investigation, D.V.D.N. and C.J.M.C.; Data Curation, D.V.D.N.; Writing—Original Draft Preparation, D.V.D.N.; Writing—Review & Editing, D.V.D.N. and C.J.M.C.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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