DEVELOPING A GEOSPATIAL METHOD FOR AUTOPILOT HARVESTER TRAMPLING EVALUATION IN COLOMBIAN SUGARCANE FIELDS

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Abstract.

Sugarcane ranks high in importance in the Cauca River geographical valley of Colombia, covering approximately 241,000 hectares and cultivated by 13 sugar mills and about 4,200 cane growers. The region's favorable climatic conditions enables the harvesting of sugarcane year-round. This, together with the high crop productivity that characterizes the region, largely attributed to technological advances developed by the Colombian Sugarcane Research Center (Cenicaña) in collaboration with regional sugar mills as well as the adoption of these innovations by cane growers, has helped position this geographical valley as one of leading sugarcane producing areas worldwide. However, increasingly efficient solutions are needed to optimize crop management and maintain these performance levels. Georeferencing and geoprocessing are both key approaches to agricultural systematization, which improve mobility of agricultural machinery, increase productive area, reduce operating costs, and prevent crop damage due to trampling by the passing of harvesters. This study accordingly aims to develop a geospatial methodology based on the parameterization of furrow geometry and harvester characteristics, which would allow the theoretical evaluation of the impact of trampling caused by autopilot-guided harvesters. This methodology uses Python programming language and aims to minimize crop damage by providing a decision-making tool that cane growers can use during the harvesting process. To assess theoretical trampling between crop rows, plots planted at a distance of 165 cm were selected and two types of rows were compared: those generated by a tractor and those obtained through UAV image processing. Results indicated that tractor-generated rows presented 0.61% theoretical trampling, while drone-generated rows presented 7.46% trampling, representing a 6.85% difference. However, it should be noted that UAV-generated rows are used in the sector for mechanical harvesting because they better reflect real field conditions by capturing sugarcane germination after planting or cutting. Based on this premise, drone-generated rows were analyzed at different stages in the same plot. Results indicated that trampling decreased by up to 2.3% with one month more of development, attributable to higher crop germination and increased precision of automatic tracing of rows. In conclusion, rows obtained from aerial images (UAV) in plots furrowed with autopilot presented a theoretical trampling of 8.42% and those furrowed with a self-guided all-in-one land prep device (cutting discs/subsoiler/rotovator), 5.59%, demonstrating that the use of this type of land prep devices for furrowing with autopilot helped reduce theoretical trampling by 2.82%.

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Keywords.
Mechanized harvesting, geospatial data, python, trampling, Saccharum officinarum

INTRODUCTION

Sugarcane is a major agroindustrial crop in Colombia, especially in the Cauca River valley where the largest area planted to this crop in the country is located, covering approximately 241,000 hectares (ha), presenting high levels of productivity (average of 102 t cane ha^{-1}) and an annual cane production around 20 million tons (Cenicaña, 2023). Because there are no defined harvest seasons for sugarcane in the region, production is year-round, which benefits both the sugar mills and nearby rural communities where most mill workers live.

In Colombia, sugarcane has a 12-to-15-month crop development cycle and, although two systems (semi-mechanized and mechanized) are used to harvest the crop, about 80% of the area planted to sugarcane in the Cauca River valley is harvested by the latter system. Self-propelled machinery is used in the mechanized harvesting of sugarcane and involves different mechanical and hydraulic systems to cut buds, make the basal cut, remove leaves and lift the harvested cane to deposit it in transport wagons. Mechanized harvesting enables the harvesting of green cane, which reduces greenhouse gas emissions caused by pre-harvest burning necessary in the case of manual harvesting (Braunbreck et al., 1999).

In addition, the implementation of controlled traffic is a necessary practice that has been adopted by the sugarcane agroindustrial sector as a high-precision alternative to sugarcane harvesting that helps mitigate soil degradation, which not only adversely affects crop productivity but also has a negative environmental impact on the agricultural production system (Ma et al., 2014). Precision agriculture techniques have been accordingly implemented, such as the use of a GNSS (Global Navigation Satellite System)-RTK (Real-time Kinematic) signal that allows the geospatial position of all agricultural machinery equipped to receive these signals to be corrected up to ~2.5 cm (Oliver, 2010). The autopilot is operated based on the corrected positioning, thus allowing the automated movement of machinery along previously established routes within the field, which, in this case, are the crop furrow lines (Kingwell & Fuchsbichler, 2011).

To obtain these crop lines, Cenicaña has developed an image processing tool for areas obtained with unmanned aerial vehicles (UAVs), which allows crop lines to be automatically generated along with other products such as depopulation segments, depopulation areas and crop development indices. Different service providers in Colombia's sugarcane agroindustrial sector offer this solution to sugar mills, and its adoption has been quite high and currently one of the main methodologies used to generate crop lines.

According to Celades-Martinez et al. (2020), the use of controlled traffic through autonomous driving is essential to reduce the field damage caused by trampling of machinery on crop rootstocks. First and foremost, controlling traffic can reduce the negative aspects of mechanization, such as soil compaction and losses in productivity due to field damage caused by trampling. This study accordingly aimed to develop an automated methodology based on the parameterization of furrow geometry, which, based on crop lines, theoretically allows a trampling percentage to be calculated prior to harvesting with the autopilot so cane growers can make informed decisions before the harvester enters the field, thus mitigating the damage caused by mechanization during crop harvesting.

METHODOLOGY

Study area

Evaluations were conducted in sugarcane fields associated with the Providencia Sugar Mill, located in Colombia's Cauca River valley near El Cerrito, with an area of influence that covers nine municipalities in the department of Valle del Cauca. Figure 1 shows the mill's sugarcane fields and the location of the sector's GNSS-RTK base stations that provide the positioning correction service to the Providencia Sugar Mill. The region's climate is classified as a dry to semi-dry mega-environment, with an annual precipitation of 870 mm, average temperatures between 18.8 and 30.2 °C, and a relative humidity of 79.4%.

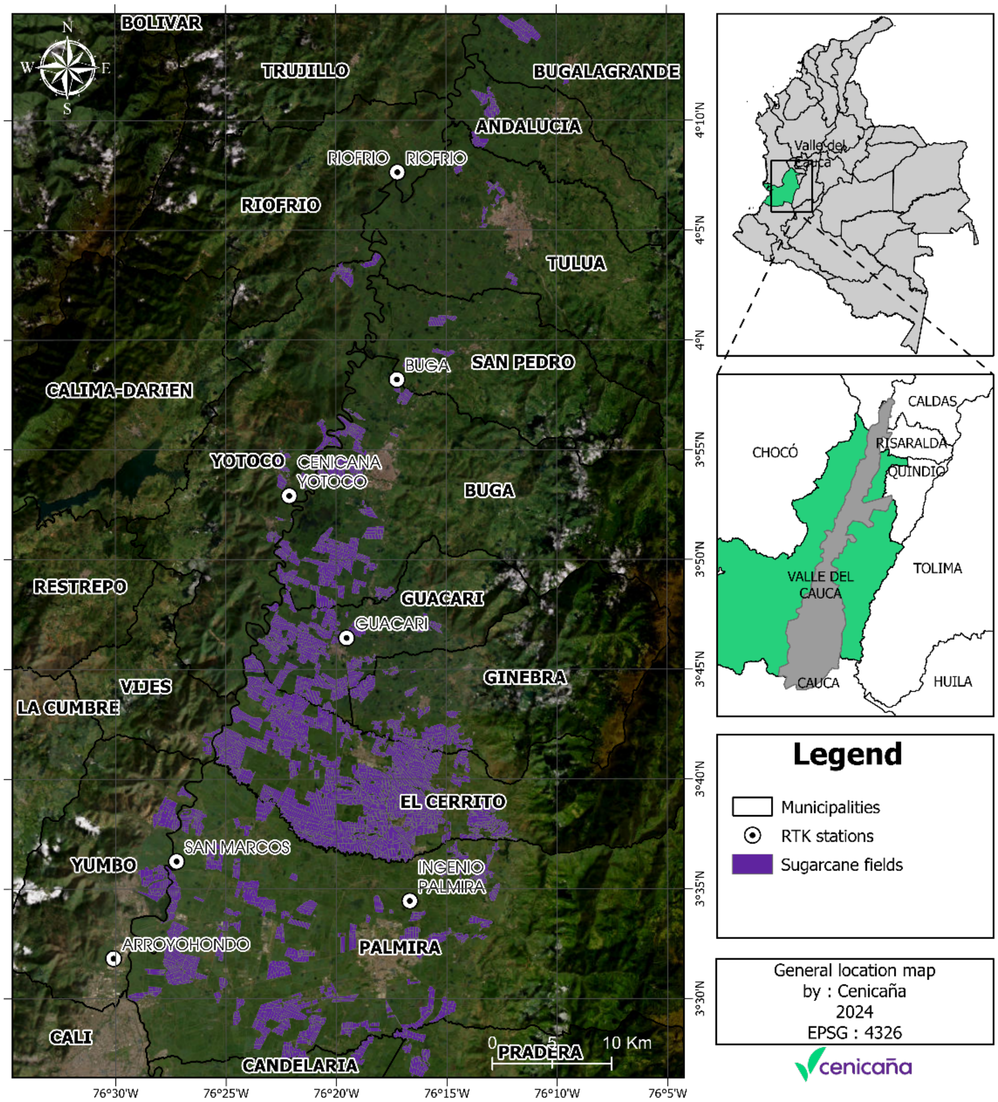


Fig 1. Study area located in Colombia's Cauca river valley.

Furrow geometry parameterization

An analytical model was proposed to study the influence of harvesting systems on sugarcane crops. The model can be used to determine the relationship between the geometry of harvesting and furrowing machinery and the trampling caused in sugarcane crops.

Geometric parameters of the furrow and field machinery in transit over the furrow were defined based on Figure 2 as follows:

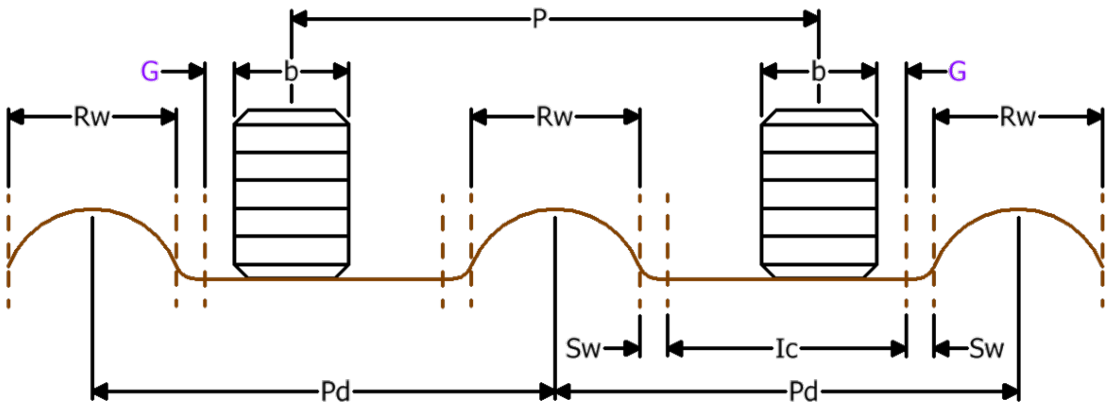


Fig 2. Furrow geometry parameterization

- P_d: Planting distance.
- I_c: Irrigation canal.
- S_w: Slope width
- R_w: Ridge width.
- P: Pathway of harvester.
- b: Tractor tire width.
- G: Clearance between furrow and harvester.

The structural parameters of furrows as well as the technical specifications of harvesting machinery should be considered to optimize the mechanized harvesting of sugarcane. The study proposes a model that estimates trampling within the sugarcane crop, a factor that can affect both soil integrity and crop yield in subsequent cycles. The model is based on the precise estimation of clearance (G), defined as the distance between the external side of the tractor wheel or track and the beginning of the furrow.

Fundamental assumptions for establishing this model include the following:

- During harvesting, the harvester moves in such a way that that its center is perfectly aligned with the center of one of the furrows. This alignment is crucial to ensure the uniform distribution of harvester weight and prevent damage to areas adjacent to said furrow.
- The analysis of trampling is restricted to the linear movement of the harvester along the length of the field, discarding transversal maneuvers that could alter the results of the model.

This methodology allows the optimization of harvest yields while contributing to the sustainability of arable land, preserving its structure and productive capacity for future agricultural cycles.

Equation 1 was used to estimate clearance (G):

$$\left(\frac{\boldsymbol{R_w}}{\mathbf{2}} + \boldsymbol{S_w} + \boldsymbol{I_c}\right) \geq \left(\frac{\boldsymbol{P} + \boldsymbol{b}}{\mathbf{2}}\right) \tag{1}$$

Where terms to the left of the equation represent the distance measured from the center of the furrow to the beginning of the adjacent furrow or ridge, and where terms to the right determine the distance from the center of the harvester to the external side of the harvester tire or track.

Based on the above, to meet the difference and estimate sugarcane trampling caused by the passing of harvesters in the field, the clearance distance (G) must comply with the difference between the aforementioned distances, thus modifying the above equation as follows:

$$G \geq \left(\frac{R_w}{2} + S_w + I_c\right) - \left(\frac{P + b}{2}\right) \tag{2}$$

Likewise, based on Figure 2, Equation 3 defines the parameter R_w as follows:

$$R_w = P_d - I_c - 2S_w \tag{3}$$

Finally, by replacing R_w with the terms of Equation 3, a simplified expression is obtained that allows clearance to be calculated based on both furrow and harvester geometry, as seen in Equation 5.

$$G = \left(\frac{(P_d - I_c - 2S_w)}{2} + S_w + I_c\right) - \left(\frac{P + b}{2}\right) \tag{4}$$

$$G \geq \frac{P_d + I_c - P - b}{2} \tag{5}$$

This way, by correlating the geometric parameters of furrow and harvester, clearance (G) is established as the criterion to estimate the trampling to the sugarcane crop caused by the passing of harvesters. Trampling does not occur when G is $\geq$ 2.54 cm as there is no contact between the tires/track and the adjacent furrow, taking into account the theoretical error of the RTK geopositioning correction. On the contrary, when G is $\leq$ 2.54 cm, the presence of trampling is imminent due to the lack of space that the wheels/tracks of the harvester have to adjust to the field design in auto-pilot harvesting.

Moreover, the irrigation canal (I_c) is a parameter that can be estimated from the information on furrow conformation and planting distance (P_d), as evidenced in Equation 6, which is obtained by removing this parameter from Equation 3.

$$I_c = P_d - 2S_w - R_w \tag{6}$$

Agricultural machinery for crop harvesting systems

Based on the previous model, it was necessary to first identify agricultural machinery used in mechanized harvesting systems in sugarcane crops to obtain information needed to evaluate the theoretical trampling caused to the crop in relation to each device. Sugarcane harvester characteristics are described below in Table 1.

These have been designed exclusively for the harvesting of sugarcane. In the case of Colombia, Case and John Deere sugarcane harvesters are used (Figure 3).

(a) Case 9900 (b) John Deere CH570

Fig 3. Sugarcane harvesters used in Colombia.

Both harvesters have similar characteristics as indicated in Table 1.

Table 1. Characteristics of sugarcane harvesters used in Colombia.

Trademark	Reference	Type of traction	Weight of harvester (tons)	Tire/track width (*b*) (cm)	Pathway of harvester (*P*) (cm)
Case	9900	Tracks	18	40.6	188
John Deere	CH570	Tracks	19.5	40.6	188

Calculating planting distance

Furrow lines are used to calculate planting distance (P_d), a key parameter to spatialize the methodology. To do so, the Colombian sugar sector implements automated methodologies based on image processing that allows the automatic generation of furrow lines from UAV images.

These furrow lines serve as input to guide mechanized harvesting with autopilot. In some cases, furrow lines are obtained by precision furrowing. Therefore, to calculate P_d, a geospatial technique was implemented that automatically measures the distance of a given furrow with respect to its neighboring furrows, allowing the evaluation of theoretical trampling of sugarcane crops due to the passing of harvesters in Colombian sugarcane fields.

To do this, a tool was developed in Python that receives the shapefile or geojson of furrow lines and obtains planting distances as follows:

1. Partitions furrows at 4-m intervals to evaluate each crop line in a detailed and precise manner.
2. When analyzing a given furrow, it selects each segment and draws a perpendicular line to the intersection with the neighboring furrow and measures the distance between both segments.
3. Repeat for all furrows to obtain a result similar to that presented in Figure 4, where red-colored lines represent the perpendicular distance between two crop lines.

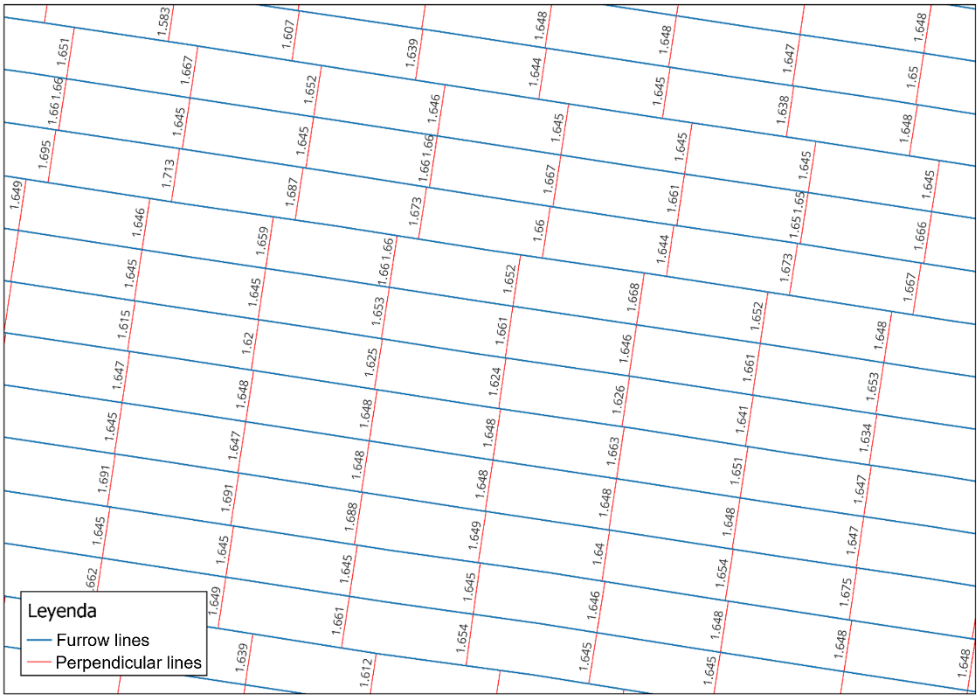


Fig 4. Graphic representation of planting distance measurement.

This process allows for the automated, large-scale determination of P_d in sugarcane plots in Colombia. The tool performs an iterative analysis for each of the lots entered, thus guaranteeing exhaustive and accurate coverage of planting data.

This tool was developed using several specialized libraries of Python programming language. In particular, “geopandas” were used to handle geospatial data, “shapely” for geometry handling and analysis, and “fiona” for reading and writing geospatial files. These libraries allow large volumes of geospatial data to be handled efficiently and accurately, thus facilitating analysis and decision-making in the agricultural management of sugarcane. Furthermore, this automation not only improves data collection efficiency, but also ensures consistency and precision by reducing the margin of human error in the process of measuring and recording planting distances.

Calculating theoretical trampling

This calculation is based on Equation 5 that involves different parameters, several of which are fixed, such as pathway of harvester (P), track width (b), irrigation canal (I_c) and planting distance (P_d) which are obtained from the previous section.

Furrow parameters such as ridge width (R_w) and slope width (S_w) are involved when estimating I_c. Currently, these two variables are fixed and obtained by conducting an intense sampling at the sugarcane agroindustrial sector level as summarized in Table 2. In this way, a formed furrow has a width of approximately 70 cm, which is the value used in Equation 6.

Lastly, the developed tool evaluates Equation 5 applied to each of the segments generated in the previous step and determines the possibility of theoretical trampling based on clearance and the comparison with the precision offered by RTK geopositioning correction systems. This tool provides users with two maps for each of the study lots. These maps indicate the parallelism between furrows and calculated theoretical trampling, serving as basis to determine the viability of carrying out mechanized harvesting without causing harmful damage to sugarcane crops in the field.

RESULTS

Most importantly, furrow geometric parameters were established for Colombia's Cauca River valley. Field evaluations revealed that a single-furrow design is used in most sugarcane crops in the region, with a ridge width (R_w) of approximately 60 cm, a slope width (S_w) of 10 cm, and an irrigation canal (I_c) width of approximately 60 cm. A furrow height between 15 and 22 cm is considered acceptable for sugarcane harvester cutting systems. Table 2 summarizes the results of 2354 samples taken from sugarcane plots with a planned planting distance of 165 cm.

Table 2. Summary of field measurements for a planting distance of 165 cm.

Field measurement	Ridge width (cm)	Planting distance (cm)
Mean	**69.19**	**170.63**
Mode	70.00	170.00
Standard deviation	**10.10**	**9.71**
Minimum	41.00	130.00
Maximum	112.00	210.00

Three planting distances (P_d) used in sugarcane crops were also identified: 150, 165 and 175 cm. Of the three, that of 165 cm was the most used. These geometric parameters are essential to optimize efficiency in mechanized harvesting and ensure adequate growth and development of sugarcane crops.

As seen in Table 2, although the fields were planned with a planting distance of 165 cm, the data average shows that, in reality, this distance is approximately 170 cm. This difference of 5 cm can be attributed to poor calibration of furrowing equipment, geopositioning errors using RTK correction, or the absence of autopilot during agricultural tasks, especially in the case of extreme data.

With this information and assuming a uniform planting distance within plots, simulations served to estimate trampling caused by the passing of harvesters with the resulting generation of correlation maps by implementing Equation 5. Clearance (G) was calculated based on both furrow and harvester dimensions, as previously explained. Table 3 presents the calculation of G for different planting distances and irrigation canal widths to establish harvester transit viability. In addition, G values > 2.54 cm are considered appropriate in view of the error control of self-guiding systems.

Table 3. Estimating clearance for different planting distances (P_d) and irrigation canals (I_c) widths.

Planting distance, Pd (cm)	Irrigation canal (Ic) width (cm)							
	70	**75**	**80**	**85**	**90**	**95**	**100**	**105**
150	-4.3	x	x	x	x	x	x	x
155	-1.8	0.7	x	x	x	x	x	x
160	0.7	3.2	5.7	x	x	x	x	x
165	3.2	5.7	8.2	10.7	x	x	x	x
170	7.0	9.5	12.0	14.5	18.2	x	x	x
175	8.2	10.7	13.2	15.7	19.5	20.7	x	x
180	10.7	13.2	15.7	18.2	22.0	23.2	25.7	x
185	13.2	15.7	18.2	20.7	24.5	25.7	28.2	30.7

Trampling would theoretically occur at this planting distance and irrigation canal width.

Trampling would theoretically not occur at this planting distance and irrigation canal width.

As shown in Table 3, harvester transit viability within crops is low for planting distances < 160 cm. In the case of a planting distance of 165 cm, irrigation canal width should be between 70 and 85 cm because the trampling of cane rootstock would be imminent with smaller widths. Because both sugarcane harvesters evaluated have the same tire and track dimensions, the trademark is irrelevant for calculating harvester transit viability.

Geospatial calculation of theoretical trampling of sugarcane by harvesters

The previous simulations that considered a uniform planting distance served as input to spatialize the analysis within each lot planted to sugarcane. The use of geospatial analysis of furrow lines to determine planting distances in different fields allowed the geospatial calculation of theoretical trampling. Different evaluations were accordingly carried out to determine the best conditions for mechanized harvesting using autopilot in terms of reducing damage due to trampling in agricultural fields.

Figure 5 presents the performance of parallelism between crop lines, generated by calculating the distance between furrows, and the theoretical trampling that could be generated by a self-guided harvester.

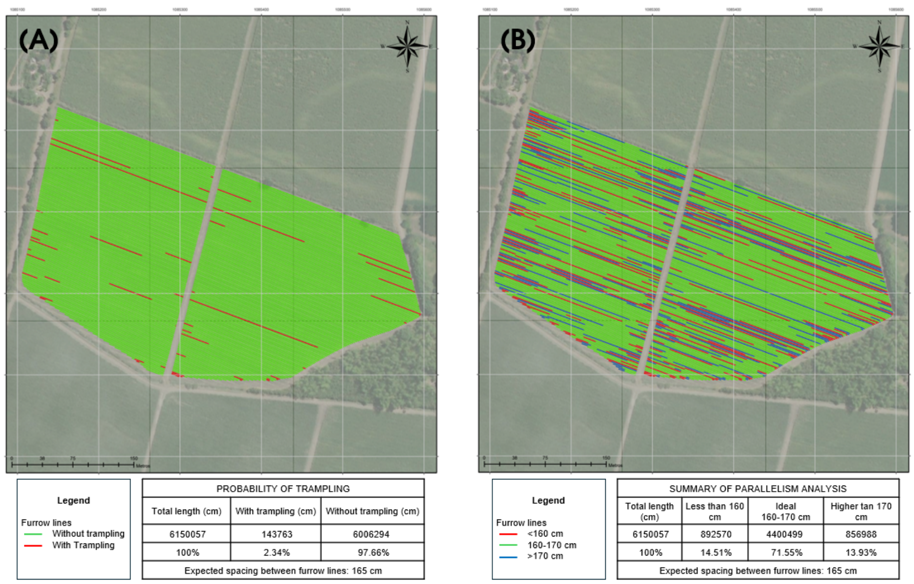
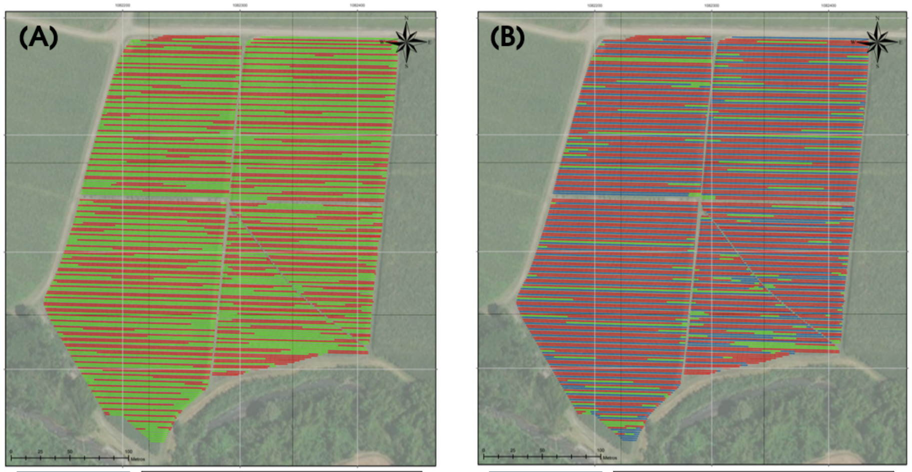


Fig 5. Theoretical trampling (A) and parallelism (B) in field furrowed with self-guided.

The lot evaluated in Figure 5 was plowed using autopilot. The calculation of trampling reflects uniformity (Figure 5A), indicating that 2.34% of the total linear meters were affected by trampling, which is very close to the ideal (0% trampling). Parallelism is high, with uniformity observed in planned planting distance throughout the crop (Figure 5B).

On the other hand, Figure 6 shows a field plowed without using autopilot. Planting distance uniformity is greatly affected and, in the ideal category, only 8% of the total linear meters achieved parallelism. Theoretical trampling that could be caused by the passing of the harvester is high in this field, with a percentage impact of 46%. This means that the harvester would trample cane rootstocks in almost half of the field.



PROBABILITY OF TRAMPLING		
Total length (cm)	With trampling (cm)	Without trampling (cm)
4536704	2104505	2432199
100%	46.39%	53.61%
Expected spacing between furrow lines: 165 cm		

SUMMARY OF PARALLELISM ANALYSIS			
Total length (cm)	Less than 160 cm	Ideal 160-170 cm	Higher tan 170 cm
4536704	2621098	404704	1510902
100%	57.78%	8.92%	33.30%
Expected spacing between furrow lines: 165 cm			

Fig 6. Theoretical trampling (A) and parallelism (B) in field furrowed without self-guided.

The abovementioned results evidence the importance of using precision agriculture in mechanized tasks to increase the uniformity of planting distance and thus reduce the theoretical trampling of sugarcane caused by mechanized harvesting with autopilot. In addition, in self-guided furrowing, the all-in-one land prep device was evaluated in self-guided furrowing to verify if the implements used influence the quality of furrowing. Figure 7 presents a comparative summary between furrowing without autopilot, furrowing with autopilot, and use of the all-in-one land prep device with autopilot.

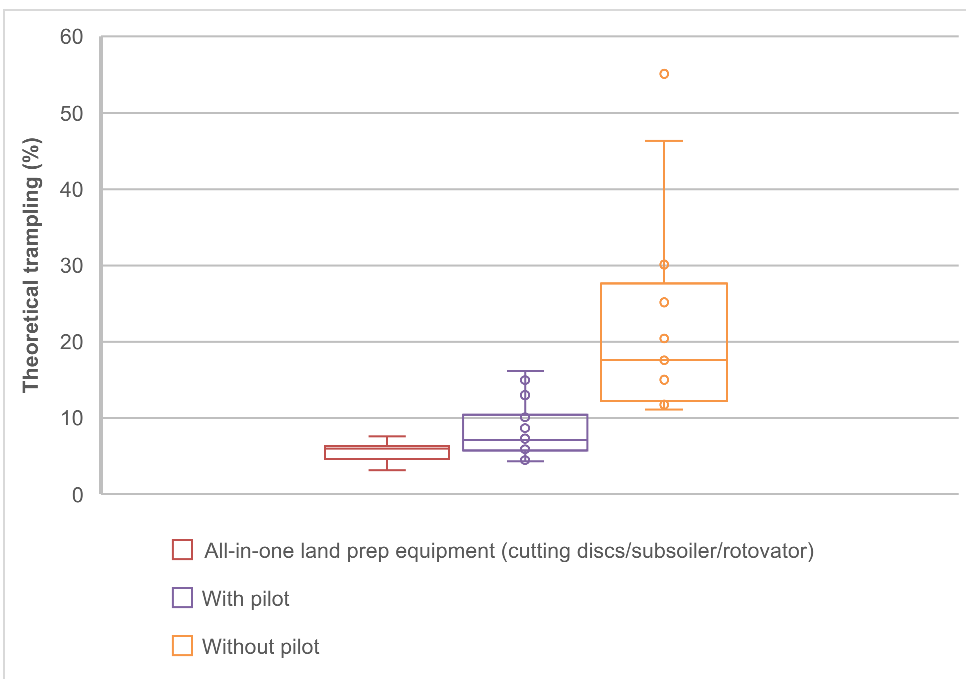


Fig 7. Percentage theoretical tramping for different furrowing methodologies.

In general, significant differences are observed when using autopilot in furrowing. Study lots that did not use precision furrowing present a theoretical trampling with an impact of 22.70%. In contrast, lots using all-in-one land prep equipment present damages of 5.59% and those that using a furrower with autopilot, damages of 8.42%. This study was carried out on a total of 785 ha of sugarcane fields, of which 267 ha were worked with a furrower, 148 ha with all-in-one land prep equipment and 370 ha without autopilot. It should be highlighted that the crop lines evaluated were generated by processing aerial images of fields planted to sugarcane between 25 and 45 days after crop harvesting.

Comparison of tractor lines in furrowing vs. lines obtained with drone images

The theoretical trampling of crop lines obtained from self-guided furrowing was compared with that of lines generated from drone images. While operating, tractors collect geospatial information that serves to generate crop lines. Significant differences are generally observed when comparing the parallelism of both types of crop lines, taking into account that tractor-generated lines represent the tractor´s trajectory while operating. However, the furrower may present different movements while operating or lack calibration, which can cause distortions that are not captured by the tractor's trajectory. Drone-generated crop lines, on the other hand, are more precise because they are extracted from a real image capture of the crop during drone flight after crop germination. The importance of crop age at the time of drone image capture will be addressed in the following section.

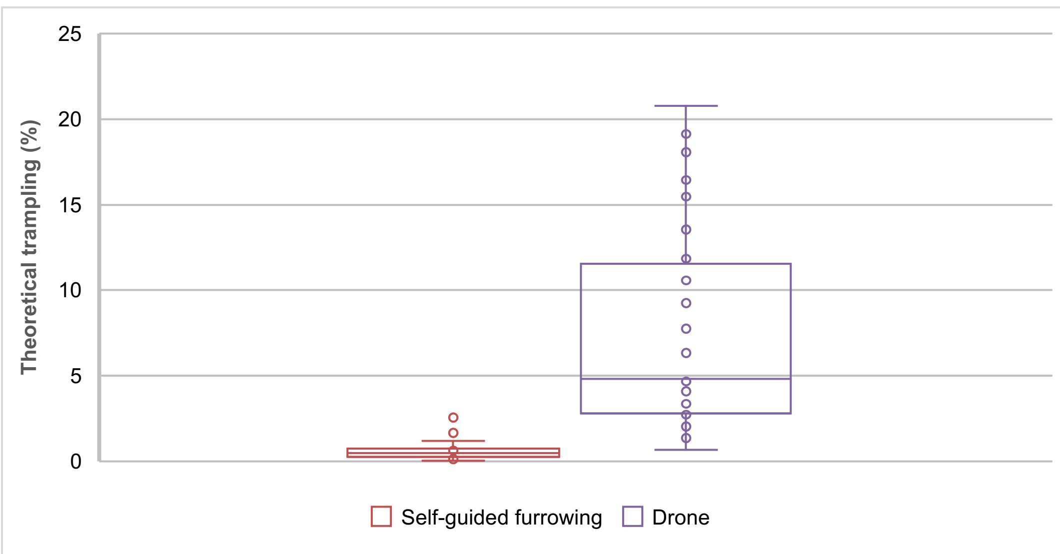


Fig 8. Theoretical trampling for pilot lines and drone lines.

Figure 8 indicates well-defined differences between both types of crop lines because the results of the pilot trajectory lines present a slight variance, which is an indicator of data consistency. The analysis of planting distance is therefore uniform over lot spatiality. Drone-generated lines, on the contrary, present a greater variance that may be due to different factors such as the effect of planting seed after furrowing, calibration errors of furrowing devices or movements of devices during furrowing that are not captured by the tractor’s trajectory.

Figure 9 presents the correlation between parallelism and theoretical trampling. A strong linear relationship is observed with a coefficient of determination $R^2 = 0.7$. Based on the regression line equation, it can be inferred that for each percentage unit of increase in parallelism there is a 0.4% decrease in theoretical trampling. This result is important and demonstrates that carrying out precision furrowing can considerably reduce trampling by the harvester when cutting sugarcane with self-guided system.

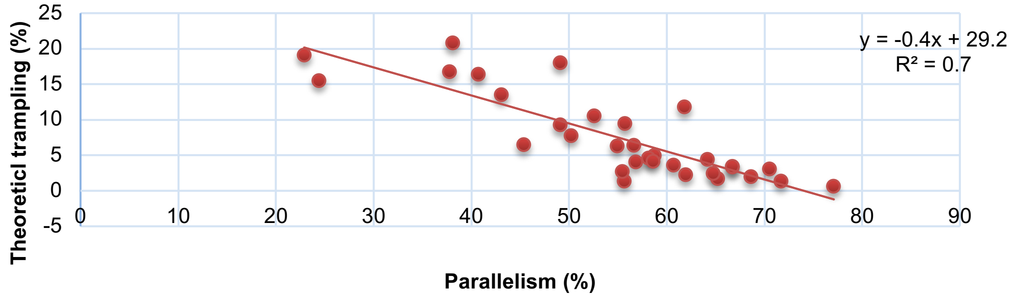


Fig 9. Performance of theoretical trampling compared with parallelism in drone lines.

Influence of crop age on timing of drone image capture

The influence of crop age on timing of drone image capture was evaluated in two sugarcane fields at the Providencia Sugar Mill. These fields were furrowed with an autopilot using an all-in-one soil preparation device. Drone flights were carried out at 30-day intervals, and the parallelism and trampling of each lot evaluated to determine the optimal age at which drone flights should be carried out to obtain the most precise crop lines.

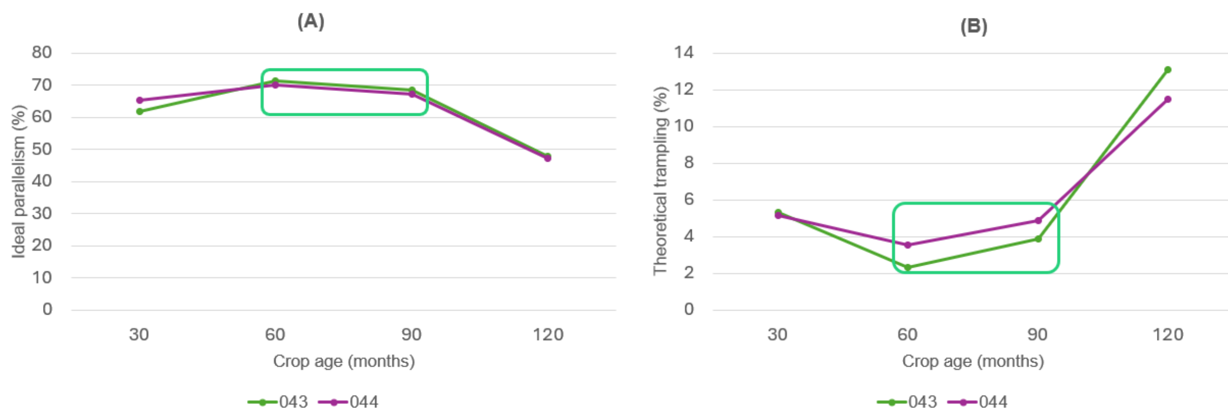


Fig 10. Comparison of parallelism (A) and theoretical trampling (B) in drone lines for different crop ages.

Based on Figure 10, it can be concluded that the recommended crop age to use drones is between 60 and 90 days after planting as lines present greater uniformity during this period. During this stage, ideal parallelism is greater than 70% and theoretical trampling is less than 4.5%, which can be attributed to the greater crop development, thus allowing image processing to detect sugarcane more accurately and reliably while also facilitating the precise tracing of crop lines.

Trampling increases to over 11.5% after 90 days. This increase is attributed to the large amount of crop biomass that closes the crop canopy, making it difficult to correctly identify the center of the furrows, thus affecting line precision.

Conclusion

This study developed and evaluated a geospatial methodology that aims to analyze the impact of theoretical trampling caused by self-guided harvesters in sugarcane fields of Colombia's Cauca river valley. The results obtained highlight several important aspects:

- The use of autopilot in furrowing significantly reduces theoretical trampling. The lots furrowed without autopilot present an impact of 22.70%, while this impact is reduced to

5.59% with the use of an all-in-one soil preparation device and to 8.42% with the use of a furrower with autopilot.

- The recommended age to carry out drone image capture flights was determined to be between 60 and 90 days after planting. During this period, crop lines present greater uniformity, with parallelism greater than 70% and theoretical trampling less than 4.5%. After 90 days, the increase in crop biomass makes it difficult to correctly distinguish the furrows, increasing the theoretical trampling to more than 8%.
- The lines generated by UAVs were found to better reflect real field conditions as compared with those generated by tractors during furrowing. Although crop lines generated by UAVs present greater variability, they are considered to more accurately capture the status of the crop, especially in early development stages.
- The implementation of precision agriculture technologies, such as the use of autopilot with corrected RTK positioning, is crucial to improve the uniformity of crop lines and reduce crop damage caused by trampling. This not only optimizes mechanized harvesting, but also contributes to arable land sustainability.

In conclusion, the development of geospatial methodologies and the use of precision technologies in mechanized sugarcane harvesting offer an effective way to minimize the impact of trampling by agricultural machinery and improve operational efficiency. Future research should focus on streamlining these techniques and exploring their applicability in different agroclimatic conditions and crop types.

Acknowledgments

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