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Geographic information technologies in the evaluation of the coffee berry borer (Hypothenemus hampei)

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Abstract

Background: Coffee is a crucial crop in Colombia, but it is threatened by the coffee berry borer, its main pest. While Cenicafé's research supports integrated pest management, and coffee growers have adopted these practices, evaluating the insect does not currently allow for the identification of hot spots due to the lack of geographic information tools.
Objective: The study aims to develop an application to support the integrated management of the coffee berry borer (Hypothenemus hampei Ferr.) by incorporating geographic information technologies into Cenicafé's pest evaluation method.
Methods: The project involves applied research conducted in four phases: - digital adaptation of the evaluation format designed by Cenicafé, - integration of the digital version of the format into an online database, - development of the geoviewer for visualization of results, and - validation of the functioning of the developed application.
Results: The project resulted in a computer application for digitalizing the evaluation of the coffee berry borer. The application includes geographic location data and presents the information in a graphic and integrated manner through a geoviewer. This aids in decision-making consistent with the integrated pest management recommended by the National Federation of Coffee Growers of Colombia.
Conclusions: The use of geographic information technologies in coffee cultivation management has been validated, particularly in the evaluation of the coffee berry borer. This opens up a range of possibilities, not only for coffee cultivation but also for other agricultural sectors.

1. Introduction

Coffee cultivation is a significant socio-economic sector in Colombia due to its high participation in exports and the large number of people involved in its production and commercialization process: “The value of the harvest [2021] closed the year at $10.8 billion, 20% more than the record of 2020, which contributes to the economic growth of the country, especially in the more than 600 municipalities and 23 departments where the bean is grown. Coffee generates some 960,000 direct jobs and has a multiplier effect on the other links in the chain: transportation, fertilizers and agrochemicals, tools and machinery, technical and professional services, etc.” [1].

The Coffee Berry Borer, CBB (Hypothenemus hampei Ferr.) is a coleopteran insect that is the main pest affecting the economic value of coffee crops worldwide, directly damaging the beans. Although its presence has been reported in African countries (specifically Gabon and Uganda) since the beginning of the 20th century, it was first observed in the American continent in 1923 in crops located in Brazil. In Colombia, it was not detected until 1988. It is important to note that the female adult penetrates the fruit to ensure the survival of its offspring. This process can cause damage to the fruit, including decreased weight, entry of microorganisms through the orifice, and fruit drop. These factors can result in a loss of quality for the bean and the final beverage.

[1] *This article is a product associated with the research work of the first author, with the direction of the second author, as a partial requirement to obtain a master’s degree in Geographic Information Technologies from the Universidad de Manizales.*

The National Federation of Coffee Growers of Colombia has defined the Integrated Management of Coffee Berry Borer, which includes a range of agronomic (cultural, biological, and chemical controls) and administrative management measures and actions. The objective is to reduce the CBB population to levels below the threshold of economic damage [2].

One of the fundamental elements for decision-making in Integrated Borer Management (IBM) is the evaluation of CBB in crops. This is done through two monthly actions and is duly recorded in the corresponding paper formats [3]:

- The calculation of the level of infestation, based on a sampling of 30 sites per hectare of crop, through a zigzag route. At each site, a productive branch is selected to count the total number of fruits and the total number of sprouted fruits.

- The determination of the position of the borer in the fruit. To achieve this, 2 or 3 sprouted grains are collected per site and opened to assess the degree of penetration. The positions are labeled as follows: - Position A: CBB initiating perforation; - Position B: CBB bit in the penetration channel; - Position C: CBB bit drilling the kernel; and - Position D: CBB bit with its offspring (eggs, larvae, and pupae).

However, this method does not allow for precise identification of pest concentration in specific areas, known as hot spots or hot spots within the lot, where localized applications of insecticides may be necessary, "not in a generalized manner, in order to protect the crop, avoid excessive use of product, environmental damage and biological imbalances" [3].

The aim of this research is to develop an application that supports the integrated management of the Coffee Berry Borer (Hypothenemus hampei Ferr.). The application will incorporate geographic information technologies to Cenicafé's method for pest evaluation. The goal is to achieve precision agriculture, resulting in more efficient and sustainable agriculture. This will benefit coffee growers of all farm sizes.

The sample size was set at two coffee lots, consistent with the exploratory nature of the study and aimed at validating the methodological procedure under representativeness criteria (altitude, Castillo® variety, climatic vulnerability, and previous infestation records). Each lot, with an area of no less than one hectare, was evaluated using the sampling density recommended by Cenicafé (30 sites/ha). In the lot at La Ofrenda farm, sampling sites were evenly distributed using a spatial grid, with points georeferenced and located in the field to ensure accurate data collection.

By contrast, in the lot at Buenos Aires farm, the location of sampling sites was determined by farm staff, considering land morphology, furrow layout, and ease of traversal, while always adhering to the required number of samples. Although the limited number of plots constrains the extrapolation of results to the entire national coffee sector, this initial approximation enables an assessment of the relevance of the sampling design and provides a solid basis for future research with broader spatial coverage.

2. Literature Review

2.1. The coffee berry borer (CBB)

The coffee berry borer (Hypothenemus hampei Ferr.) is the primary coffee pest worldwide "due to the fact that it can cause several types of damage: 1- Fall of small fruits (decreases production volumes), 2- Losses in weight (affects the yield factor) and 3- Losses in quality (affects the sale price of coffee)" [4]. Climate warming could increase the impact of these issues by 5 to 10 times more, as it could reach the optimum maximum of 26°C in more coffee growing regions [5], this is concerning as it could lead to changes in the organoleptic characteristics of the final beverage. According to [6], an infestation increases of 1% results in a premature fall of beans between 0.26% and 0.47%, while infestations ranging from 10% to 15% cause losses of approximately 5 kg for every 46 kg of coffee.

The CBB is a holometabolous insect with distinct life stages: egg, several larval stages, pupal, and adult. Sexual dimorphism is present, with males measuring 1 to 1.25 mm long and 0.5 to 0.6 mm wide, and females measuring 1.37 to 1.82 mm long and 0.62 to 0.80 mm wide. Males have membranous wings that do not allow them to fly and live between 20 and 87 days, while females can live up to 157 days and can invade fruits different from their birthplace [7]. The accepted ratio for successful reproduction is one male to ten females. Parthenogenesis has been ruled out, and the identification of genes expressed in males suggests that the Y chromosome may be involved in haplodiploidy in insects [8].

In addition, the CBB is an insect that is native to the Guinean Congolese forests, with altitudes ranging from 0 to 1,200 meters and an average temperature of 24 to 26°C. It is commonly found in areas where Coffea canephora 'Robusta' is predominant and has since spread to other parts of Africa. Cryphalus hampei was first described by Johann Angelo Ferrari in 1867 from beans that were exported to France [8]. However, after a comparative analysis between species of the genera Stephanoderes and Hypothenemus, it was relocated to the genus Hypothenemus by Costa Lima in 1928 [2]. Currently, it is taxonomically classified as Hypothenemus hampei, a species in the subfamily Scolytinae of the family Curculionidae, order Coleoptera, class Insecta or Hexapod.

2.2. Integrated Management of coffee Berry Borer, IBM

The National Federation of Coffee Growers of Colombia has implemented the integrated management of the coffee berry borer (IBM) in Colombian coffee growing based on research conducted by its Coffee Research Center, Cenicafé, since the 1990s. Within the IBM, evaluating the level and position of the coffee berry borer (CBB) in the lots is crucial for this work:

- To estimate CBB infestation levels, we recommend using the method transferred to coffee growers. This should be done fortnightly after harvesting, and for each hectare of crop, a zigzag route should be taken. 30 trees or sites should be chosen, and from each, a productive branch should be selected. Count the total number of fruits and sprouted fruits and calculate the infestation level by multiplying the total number of sprouted fruits counted by 100 and dividing this result by the total number of fruits counted [9].

To evaluate the position of CBB penetration in the fruit, 100 fruits were randomly collected and the position of the CBB was determined in each. The number of live and dead adults and their location inside the fruit were determined through dissection. The positions are: - Position A refers to when a borer is searching for or initiating its perforation of a fruit. - Position B is when a borer is located in the penetration channel. - Position C is when the borer is perforating the kernel. - Position D refers to a borer with its offspring, including eggs, larvae, and pupae [2].

It is important to note that various coffee guilds have implemented different strategies to support the establishment of the IBM and prevent significant damage to the productivity and quality of Colombian coffee caused by this pest. An example of this is a foldable (Fig. 1) that visually integrates the development of the fruit, the development of the insect, the damage caused by the insect, and the recommended management practices. This tool was designed to enhance the understanding of Colombian coffee growers who received training at the Agricultural Education Center of the Manuel Mejia Foundation

2.3. Some background

In the coffee sector, geographic information technologies have been incorporated into the management of exploitation in some cases. It is worth mentioning these experiences:

This study evaluated the spatial distribution of Hypothenemus hampei Ferrari in coffee agroecosystems in the central jungle of Peru under different states of floristic diversity. Diversity indices were used to analyze the distribution of insects, and the Kernel density with ArcGIS software was used for spatial analysis. The results showed that the distribution of insects was conditioned towards sectors with greater vegetation and shade [11].

A GIS was implemented in a coffee farm located in Belalcazar (Caldas, Colombia) with the support of ArcGIS and Google Earth tools. The GIS was based on satellite images and field data collection. An application was used to provide the costs corresponding to five cultural activities, namely weed control, fertilization, CBB control, harvesting, and other tasks. Additionally, the application provided the levels of CBB infestation, for which the method designed by Cenicafé was used [12].

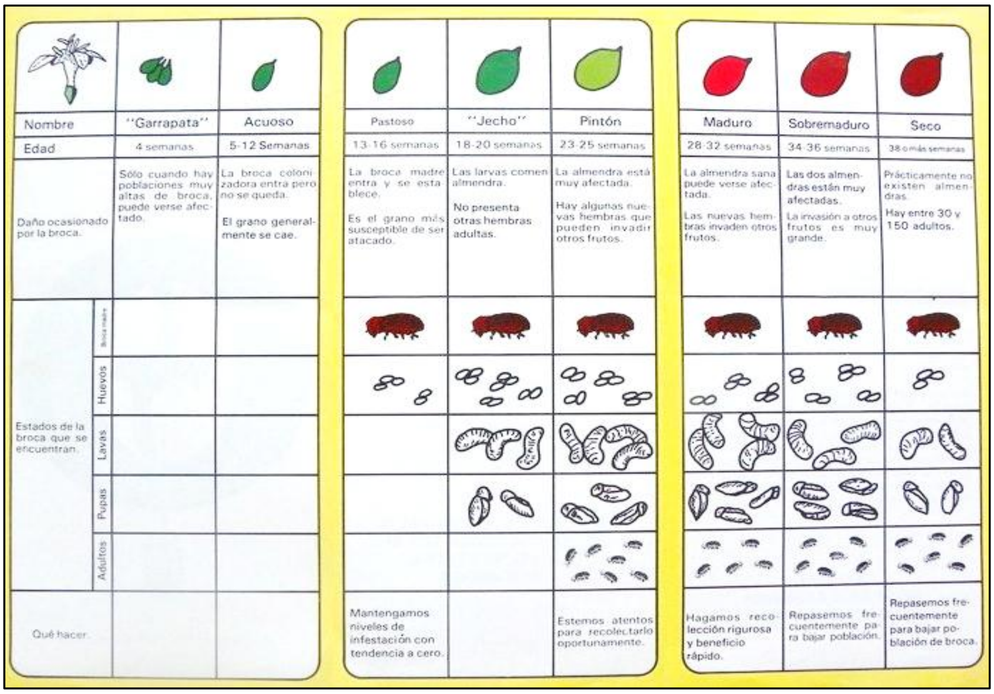

Fig. 1 Foldable integrating coffee fruit development, CBB, damage caused and management. [10]

At Cenicafé, research has been conducted on the vulnerability of coffee plantations to CBB in different climatic events. The research takes into account the favorable temperatures for greater dispersion and the shortening of the life cycle of H. hampei. Maps have been created from meteorological information using advanced techniques and geographic information systems and ArcGIS software. Several studies have been conducted in coffee ecotopes across the coffee-growing country, including the departments of Risaralda [13] and Huila [14]. These studies provide valuable information on MIB levels during different periods, such as the presence of El Niño or La Niña phenomena.

A physiology-based dynamics model (PBDM) of the coffee agroecosystem in Colombia has been integrated with GIS GRASS or QGIS systems. This allows for the creation of maps and analysis of the effect of climate on flowering, crop production, and CBB dynamics [15].

A mathematical simulation model for coffee cultivation with a predictive character, including vegetative and reproductive growth, leaf development, dry matter distribution, fruit growth and production, based on Cenicafé research and as a key element for crop forecasting and decision making [16].

Alves et al. [17] analyzed and characterized the spatial patterns of infestation by CBB and the leaf miner (Leucoptera coffeella) in a coffee agroecosystem using advanced geostatistical techniques and geographic information systems (GIS). The methodology used two approaches to create variograms: the method of moments (MoM) and residual maximum likelihood (REML). Comparison of the two approaches revealed that REML estimates were superior in terms of the accuracy of the error coefficients in the kriging process. Additionally, weighted ordinary least squares (OLS) adjusted variogram models were applied to the MoM experimental variogram, which enabled mapping of the spatial and temporal variation of pest infestations.

A system for monitoring and diagnosing the presence of coffee rust (Hemileia vastatrix) has been developed. The system integrates the electronics of five meteorological stations, radiofrequency transmission established by mobile telephony, and a web platform service for the storage and subsequent analysis of data. The validation of this system led to the visualization of the incidence and severity of rust on plant leaves [18].

Chemical control is one of the most critical aspects of agronomic crop management, including CBB management. It has direct implications for environmental health, including the applicator and possible residues in the final product (in the case of coffee, for human consumption), as well as the efficacy and safety of the application. Several factors must be considered for effective chemical control. Therefore, when it comes to MIB, the decision to use chemical insecticides should be based on a prior evaluation of the CBB and be recommended by a professional agronomist. Additionally, it is important to consider actions aimed at reducing risk, such as selecting the appropriate insecticide product based on its toxicological category, the type of crop, the type of action, and the type of application. Proper transportation and storage of pesticides, calibration of spraying equipment and applicator, dosage and preparation of the insecticide, protection of the applicator and the environment, and proper disposal and management of residues and packaging are also crucial. Several regulations exist in Colombia regarding agricultural health, particularly from the Colombian Agricultural Institute (ICA), the government agency responsible for overseeing this area.

3. Methodology

The applied research project was executed in four phases: - digital adaptation of the evaluation format designed by Cenicafé, - integration of the digital version of the format into an online database, - development of the geoviewer for visualization of results, and - validation of the functioning of the developed application.

A digital form was designed to meet the specifications of the field assessment process. This form was divided into three groups of data: auto-complete data, user-entered data, and data for internal processing. ArcGIS Online was used to integrate the digital version of the form into an online database, creating a cloud folder that stores the structure of the form, as well as a layer in vector format that links the table to the points using coordinates (X, Y) based on the WGS84 datum. This layer has become an online service that allows remote access to the data and its consultation through the configuration of a web map.

Design guidelines (clarity and focus, organization and structure, symbology and values, interactivity, responsive design and compatibility, smart tags, updating and maintenance, browser compatibility, security and permissions) have been applied in the development of geoviewer, an essential tool for visualizing the results obtained in the field, in order to ensure an optimal user experience and effective presentation of the information. To implement geoviewer, ESRI's Experience Builder was selected and tested, covering the entire process from feeding the system with information collected in the field to selecting data through filters.

The field work to validate the operation of the application was carried out in the municipality of Pereira (Risaralda, Colombia), in the township of Arabia, specifically in the farms La Ofrenda (lot El Plan with an area of 15,346 m2 or 1.53 ha) and Buenos Aires (lot N1 Cementerio with an area of 11,108 m2 or 1.11 ha), with centroid coordinates 75.744139°W; 4.754866°N and 75.717429°W; 4.71547°N, respectively, in the optimal coffee growing zone and planted with the Castillo variety. In the field, electronic devices were used, such as a laptop for programming the digital form and the geoviewer (Fig. 2).

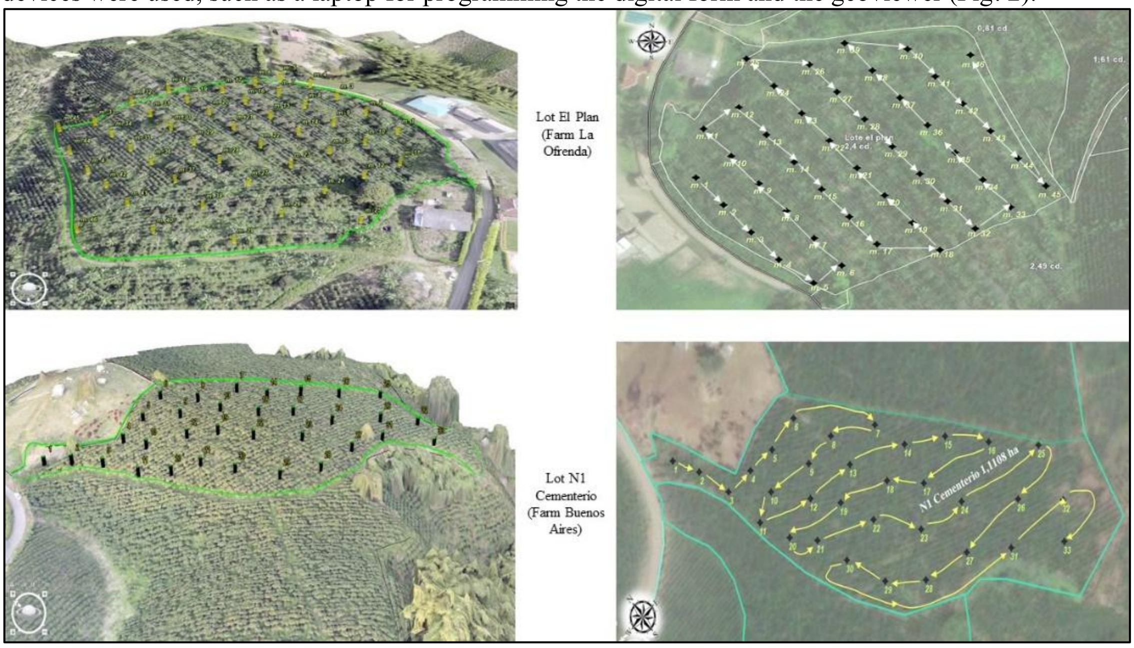

Fig. 2 Distribution of the sampled plants and the route through the lots

In addition, smart phones were used to collect data and GPS devices were used to accurately record the locations of the sampling units (Fig. 3).

Fig. 3 Validation of the functioning of the develop application

4. Results

For the corresponding digital form (Fig. 4), the variables were grouped into three groups: - data managed by the system itself (date, time and GPS accuracy of the mobile phone), - data managed by the user (fields that the evaluator or field technician enters into the device based on his observations on each plant: number of fruits, number of affected fruits, location of the CBB in the fruit) and - internal processing data (based on the configuration of formulas for information processing).

These groups of data are in turn classified under two headings: - the front-end, which groups the data displayed and which users can view or edit directly in an interface, and - the back-end, which is responsible for data processing and storage, as well as for the logic and functionality that supports user interaction in the front-end. Together, they work in an integrated fashion to provide complete and functional form experience, which was loaded into the Survey123 Connect application with a total of 99 fields.

The results of the CBB evaluation process, based on a total of five evaluations conducted in each of the farms, are presented in Table 1. The field data collection process takes on average, 03 minutes and 14 seconds per plant, depending on the number of fruits per branch, the number of fruits affected by CBB, the topography, among other factors.

The application makes it possible to visualize the information obtained in the field, including hot spots, geographically (Fig. 5) and even to display the history and alerts (Fig. 6), based on Cenicafé's recommendations, according to the level of infestation and the position of the CBB in the fruit. In this way, coffee growers can make timely, differentiated and localized management decisions with agronomic, economic and environmental implications.

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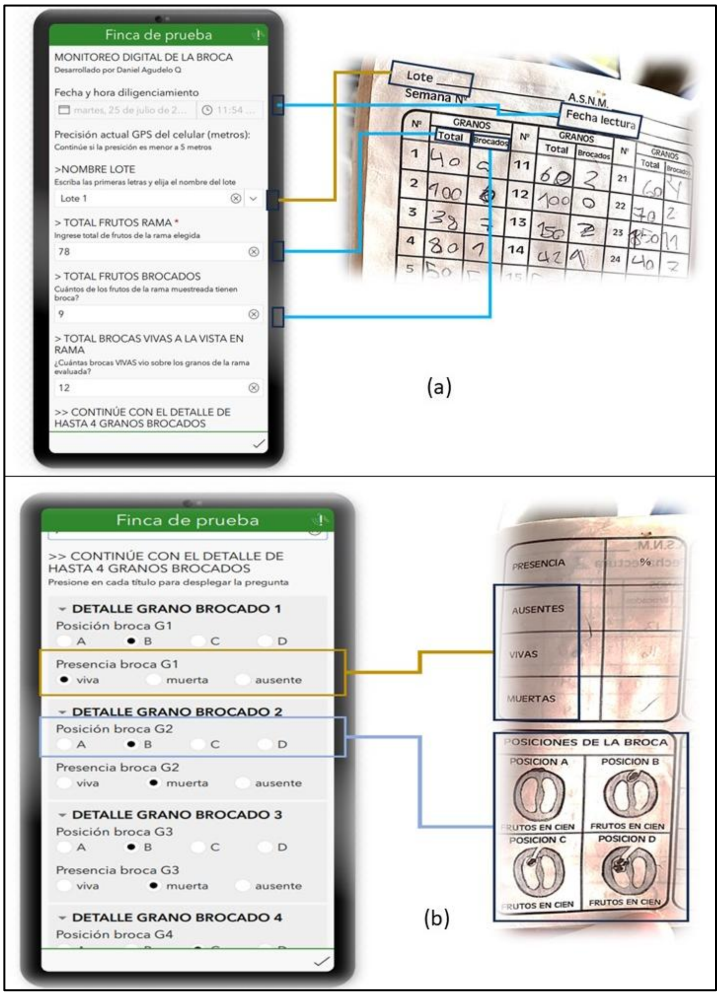

Fig. 4 Adaptation of the digital form with the variables for the analog assessment of infestation level (a) and CBB position (b)

Table 1 Results of CBB assessments in La Ofrenda and Buenos Aires farms

			Evaluation date (2023)				
			June 10	**July 01**	**July 05**	**July 29**	**August 12**
Lot El Plan Farm La Ofrenda	Number of plants sampled		46	46	46	46	46
	Average time in minutes per sample (hh:mm:ss)		00:03:22	00:03:26	00:02:35	00:04:26	00:02:49
	Evaluation variable	% CBB infestation (lot)	7,9%	11,7%	13,7%	12,2%	13,1%
		% live CBB in A or B positions	29%	50%	10%	11%	16%
	Other calculations obtained during evaluation	Total grains	2699	2220	2175	3959	2505
		Total drilled kernels	219	260	297	483	327
		Total trees with borers	40	46	45	44	46
		Average kernels per branch	59	48	47	86	54
Lot N1 Cementerio Farm Buenos Aires	Number of plants sampled		33	33	33	33	33
	Average time in minutes per sample (hh:mm:ss)		00:03:35	00:02:45	00:03:10	00:02:58	00:03:04
	Evaluation variable	% CBB infestation (lot)	4,0%	6,2%	6,5%	1,9%	7,4%
		% live CBB in A or B positions	8%	25%	38%	3%	9%
	Other calculations obtained during evaluation	Total grains	1942	1545	1680	2734	1635
		Total drilled kernels	77	96	109	52	121
		Total trees with borers	17	29	31	22	32
		Average kernels per branch	63	47	51	83	50

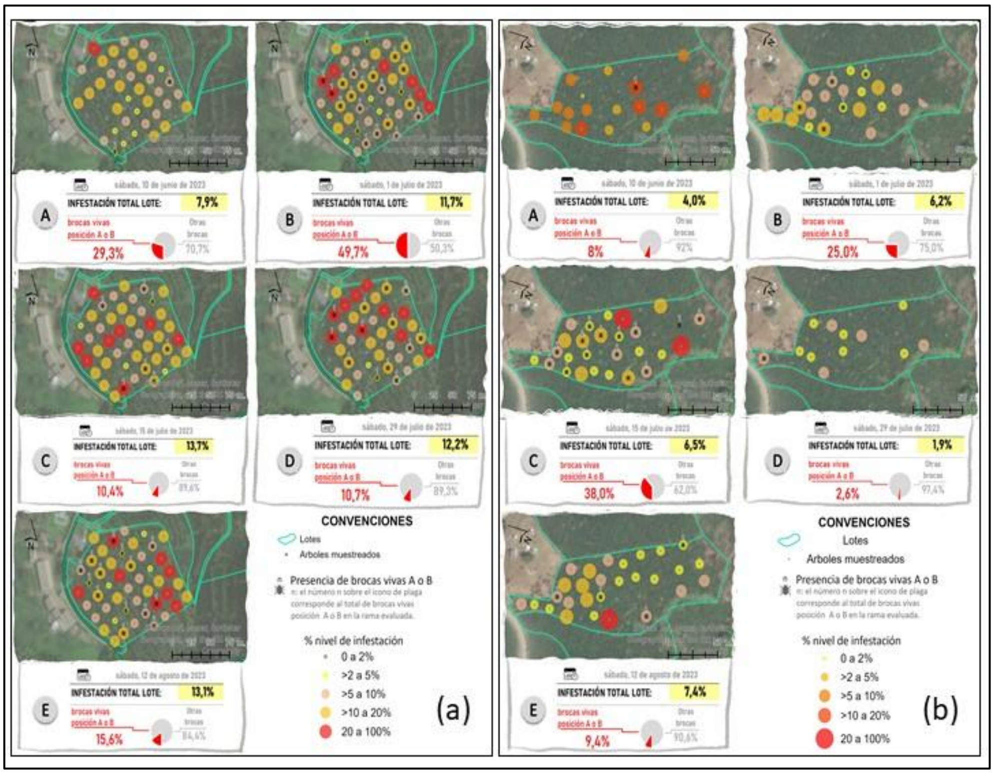

Fig. 5 Geographical representations of the results of CBB evaluations in La Ofrenda (a) and Buenos Aires (b) farms

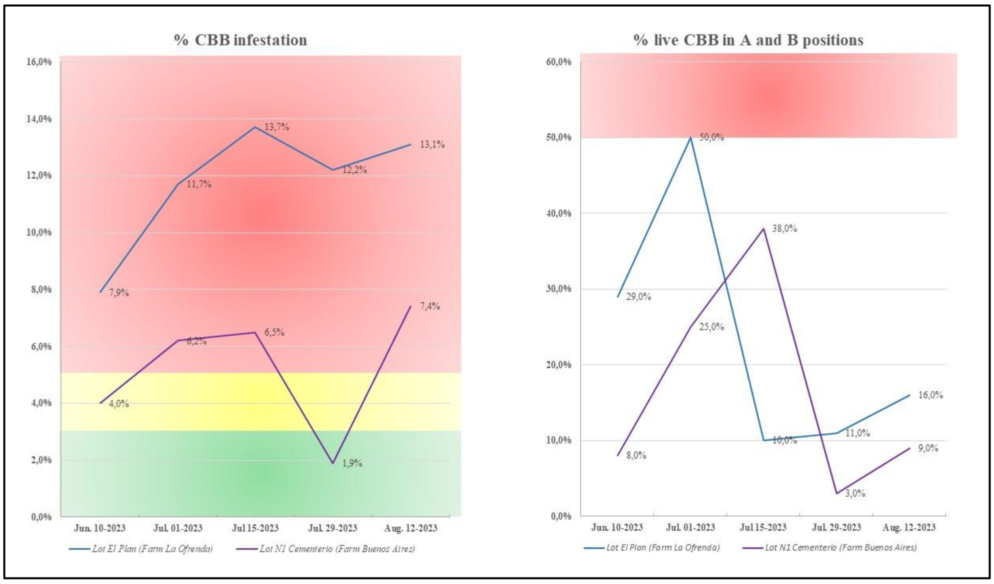

Fig. 6 Historical results of CBB evaluations in La Ofrenda and Buenos Aires farms

The versatility and utility of the ESRI product suite in the context of MIPapa application development [19], it is evident that the adaptation of customized technology tools that allow the linkage of tabular data with geospatial information provides a powerful set of capabilities for integrated crop pest management. This approach is confirmed by this research for CBB monitoring in coffee crops. In addition, while MIPapa used ExperienceBuilder, this project relied on WebAppBuilder, which allowed for the inclusion of widgets and features tailored to CBB assessment query needs, including the ability to filter by lot name and assessment date, thus facilitating the monitoring review process.

The incorporation of geographic information technologies and spatial analysis opens up new opportunities for progress towards more efficient, sustainable and resilient coffee production. From this perspective, the advancement of geostatistical analysis with the aim of characterizing the spatial patterns of infestation can be considered as the next step in the trajectory of this research, following cases of implementation in other countries [11], [17].

As a summary of the project, Table 2 presents each of its phases, indicating what was done and achieved in each one.

Table 2 Project phases with their description, tools used, and results obtained

Phase	Description	Tools used	Products / Results
1. Adaptation of the coffee berry borer (CBB) infestation assessment format (analog to digital)	Literature review, synthesis of Cenicafé's method, design of the evaluation workflow, creation of the digital form, and usability testing.	Documentary review; methodological matrix; flowcharts; Survey123 Connect®; xlsForms; interface mockups; desktop testing.	Methodological matrix; evaluation process flowchart; digital ENIB form (99 fields, front-end and back-end); preliminary usability tests.
2. Integration of the digital form into an online database	Configuration of the storage structure and synchronization in the cloud.	Cloud-based spatial database; synchronization services; ArcGIS Online®.	Online geospatial database; structured repository of evaluations; remote availability of information for queries and analysis.
3. Development of the geoviewer for results visualization	Conceptual design and implementation of an interactive viewer; testing on desktop and mobile devices.	ArcGIS Experience Builder® (ESRI); Map Viewer; configured symbology and filters.	Functional geoviewer to query results by plot and date; clear visualization of infestation and penetration; near-instant results for field users and decision-makers.
4. Field validation of the developed application	Testing in La Ofrenda and Buenos Aires farms; user training and support; error detection and improvement.	Mobile devices in offline mode; Survey123®.	Validation in real production units; user feedback; evidence of system relevance and scalability.

5. Discussion

The versatility and utility of ESRI's suite of products in the context of MIPapa application development [19], it is evident that the adaptation of customized technology tools, which allow for the linkage of tabular data with geospatial information, provides a powerful set of capabilities for integrated crop pest management. This approach is corroborated by this research for CBB monitoring in coffee crops. In addition, unlike MIPapa, ExperienceBuilder®, released in July 2019, was used instead of WebAppBuilder®, which allowed the inclusion of widgets and functions aligned with query needs for assessing CBB, including the ability to filter by lot name and date of assessment, thus facilitating the monitoring review process.

Although the work was done respecting the recommendations of the MIB designed by Cenicafé, there is the possibility of considering the established thresholds, the stage of development of the fruit and the presence of the pest, based on alternatives such as those proposed by Kawabata, Nakamoto and Curtiss [20].

The incorporation of geographic information technologies and spatial analysis open new opportunities to advance towards a more efficient, sustainable and resilient coffee production. From this perspective, the advance in geostatistical analysis, with the purpose of characterizing spatial patterns of infestation, can be considered as the next step in the trajectory of this research, following cases of implementation in other countries (e.g., Alves et al. [17], or Alvarado [11]). Thus, additional variables to the current evaluation could be considered, taking advantage of the geographical location, such as the altitude of the lot, microclimatic aspects, meteorological conditions of the last days, among others, that influence the behavior of the crop and the pest. In this line, antecedents in the departments of Risaralda and Huila [13], [14] can serve as a starting point.

Despite demonstrating the methodological feasibility of integrating geospatial technologies into coffee berry borer (CBB) assessment, this study has limitations regarding sample representativeness (restricted to two coffee plots), spatial and temporal scope (a single region and five assessment cycles), and the extent of technological implementation (focused on data capture and visualization rather than predictive analytics). Accordingly, the findings should be interpreted as exploratory and indicative of this approach's potential, rather than conclusive for the entire Colombian coffee sector. Future research should broaden geographical coverage, incorporate additional agroecological variables, and evaluate the system under diverse operational contexts to reinforce its scalability and generalizability.

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6. Conclusions

This work validates the possibility and relevance of incorporating geographic information technology in coffee crop management, specifically in the evaluation of CBB, and opens a wide range of possibilities to further enrich this approach. Therefore, digitizing the assessment has not only proven to be more efficient but also opens up a wide range of possibilities thanks to geospatial, computing, and communications technologies.

While it is feasible to digitally assess coffee berry borer infestation and penetration positions using geographic information technologies, there is a recognized need to improve tools to increase efficiency in determining the borer's penetration position in infested beans.

The use of the geoviewer demonstrates the feasibility of consulting the results and sending them directly to decision-makers, to improve the relevance and timeliness of their management. In the context of small-scale agriculture, which represents the majority of coffee producers in Colombia and other coffee-growing countries, the implementation of geospatial technologies for CBB monitoring can have a direct and tangible impact.

By facilitating timely access to field data, reducing monitoring costs, and enabling more precise pest control, these tools strengthen the capacity of smallholders to safeguard yield and quality. Furthermore, their applicability under conditions of limited resources or connectivity enhances the potential for farmer associations and cooperatives to collectively improve resilience and sustainability in coffee production.

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