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POPULATION DYNAMICS OF THE COFFEE BERRY BORER (*Hypothenemus hampei* FERRARI, 1867) IN THE STATE OF MEXICO

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RESUMEN

Coffee, as one of the main agricultural products consumed worldwide, has acquired a very important role in agriculture this crop, as well as other economically important crops, is attacked by various pests and diseases, among them, the coffee berry borer has become the most important coffee pest worldwide, due to its effects on the crop, causing losses to coffee growers due to reduced yields, drop of unripe fruits and reduction of their quality, for the present research, the behavior of the Coffee berry borer was identified using the population dynamics tool, in order to determine the current state of the populations, for this reason sampling was carried out in four municipalities of the State of Mexico, Mexico, the Bootstrap method was used to validate the accuracy of the data, since it allows us to estimate the statistics of interest in order to use them in different models, which were: Weibull, Richards, Morgan and Multiple Linear Regression, where the best model to estimate the distribution was the Weibull model, since the selection of this model was due to the accuracy of the data obtained and its complexity, as a result of the model the growth rate of the insect and its amplitude in the study area were observed, observing an exponential growth, reaching an infestation of 50% of the plots in one year of simulation, showing that from day 200 the infestation begins, reaching the conclusion that the environment of these zones is ideal for the pest to proliferate, this helps crop management to anticipate and control the spread of the pest by adjusting the control practices.

KEY WORDS: Coffee plantations, Pest control, Simulation, Weibull model, Coffee

INTRODUCTION

Coffee is one of the most important agricultural products consumed worldwide (Medina-Meléndez et al. 2016), this product is positioned in second place as a raw material, only behind crude oil. At world level coffee has acquired great importance due to its total commercial value, which reached 16.5 billion dollars in 2010 (Figueroa-Hernández et al. 2016).World coffee production and supply is divided into two main types, defined by the variety cultivated: arabica and robusta; in the world market, the majority sector is arabica coffee (Leguizamo-Sotelo et al. 2023).

Coffee production is an activity of economic relevance that is carried out in more than 52 countries (Rivera-Rojo, 2022). The countries with the largest coffee production in the world are Brazil, Vietnam, Colombia, Ethiopia and India (Ocampo-López and Alvarez-Herrera, 2017). In Mexico, the states of Veracruz, Chiapas and Oaxaca are the states with the largest coffee production, accounting for close to 80% of the total production (Alfonse, 2018). The State of Mexico was the twelfth largest producer in 2014, with 427 t (0.04% of the national total) (González-Razo, 2019).

The coffee crop, like other agricultural products, is attacked by pests and diseases, among which the coffee berry borer, *Hypothenemus hampei* Ferrari, 1867 (Coleoptera: Curculionidae: Scolytinae), stands out, according to Constantino et al. (2021) this is the most important pest of the coffee crop in the world. Coffee berry borer infestation occurs after emergence, where each young fecund female, known as a founder, moves towards a coffee fruit, perforates it, making a circular hole as well as forming tunnels and galleries as she feeds on the endosperm (Molina, 2023). Coffee berry borer females perforate the fruit and build galleries inside it, causing damage such as fruit drop and loss of bean weight. Although there are alternatives for their control, they are sometimes costly, which limits coffee growers to adopt them (Donato-Ortiz, 2018). Worldwide, the Coffee berry borer is estimated to cause annual losses of more than US$ 500 million (Castrillon, 2017). Damage caused by *H. hampei* causes at least three types of losses to coffee growers: reduction in yield due to partial or total damage to parchment coffee, fall of immature fruits and reduction in quality. In the first loss, Coffee berry borer infestation causes a reduction in the weight of parchment coffee of between 10.82 and 45.12 % (Molina, 2022). Its importance lies in the fact that the adult bores the kernels and reproduces inside the endosperm, causing total or partial loss of the kernel (Constantino et al. 2021), although the importance of the pest, the studies on different aspects of its biology, integrated management and control methods, very little research has been done on the population dynamics and ecology of the insect in coffee crops.

Population dynamics is a tool for linking biological data in the short term as it can be used to determine the current status of populations and can potentially be a component for their management and conservation (Martínez-Ramos, 2016), with respect to the population dynamics of the Coffee berry borer, this is important because studies have been done in which more Coffee berry borer infestation has been reported in crops with free exposure than under shade, also suggesting that lowering the temperature can keep Coffee berry borer populations in shaded crops below the level of those found in crops with free sun exposure and greater diversity of shade trees lower the population density of the Coffee berry borer (Constantino et al. 2021). Globally, these changes in temperature increase may cause adaptive changes in insect populations between different altitudinal ranges, such as changes in the behavior with their hosts, generate alterations and lags in the synchronization of periods of activity of host and parasitoid insects (Constantino et al. 2011). Climatic alterations, together with the felling of shade trees, cause the weakening of the plants, which makes them more susceptible to damage by various pests (Beristain-Moreno, 2024).

To estimate the sample distribution and evaluate its precision, the Bootstrap method was used, which consists of taking multiple samples with replacement of an original sample. This allows estimating statistics of interest and constructing confidence intervals without assuming a specific distribution for the population. From these samples, the mean of the statistics obtained is calculated to estimate the final statistic and confidence intervals are constructed using percentiles (Solanas, A., and Olivera, V. 1992).

In addition, three models were evaluated to determine which best explains population dynamics: Weibull, Richards and Multiple Linear Regression. The Weibull model is flexible for adjusting mortality rates that change over time, the Richards model is useful for describing nonlinear growth rates, and multiple linear regression helps to identify relationships between multiple factors and a dependent variable (Velasco-Hernández, 2020).

Therefore, the objective of this study was to analyze the population dynamics of the coffee berry borer (*Hypothenemus hampei*) in coffee plantations in the State of Mexico, evaluating abiotic factors that influence its proliferation through the phenological stage of coffee, in order to develop effective integrated management strategies for its control and to mitigate the economic impacts on coffee production.

MATERIAL AND METHODS

Data collection

The study was carried out by means of Coffee Berry borer trapping during the months of January to December 2023, traps were placed in four municipalities with different altitudinal strata in order to make a phytosanitary cordon to identify the limits of free zones, and those with presence of Coffee berry borer in the municipalities of: Amatepec, Sultepec, Tlatlaya and Tejupilco in the State of Mexico, Mexico, in this region, during the summer months, temperatures range between 22 and 24 °C, with average rainfall peaking in June (more than 200 mm), decreasing towards the end of the year, the month with the highest humidity is September, exceeding 80 %. The dry season, on the other hand, occurs in December, with very low rainfall and temperatures close to 16 °C (Rosendo-Chávez, 2019). The traps used were of the ECO-IAPAR handmade type, with an attractant of methyl alcohol and ethyl alcohol in a 3:1 ratio (SENASICA, 2019). The traps were checked every 30 days during the evaluation period, the coffee crop was of different cultivars, including caturra and typica, with an average age between 5 and 20 years (Suárez-Albarracín, 2018).

Bibliographic data collection

Literature related to the identification of the most appropriate simulation models to determine the population dynamics of insects was reviewed, such as the work of (Bustillo-Pardey, 2006; Molina, 2022; Bacca *et al*. 2021; Chuaire *et al*. 2024), from these analyses, it was determined that the inclusion of climatic conditions is critical as a penalty factor in insect survival models. This is because climatic variables, such as temperature and precipitation, directly influence the life cycles and mortality of pests, affecting the accuracy in the simulation of their populations. The selected model incorporates these conditions as constraints to adjust survival predictions, which improves the efficiency and realism of the simulations.

Data Analysis

Normality of data.

With the data obtained in the field, a database was created in a spreadsheet in Microsoft Excel 2023 software, to later process the information in Python (version 3.12.6), the estimation of the sample distribution was done through the Bootstrap Model estimation, which consists of taking multiple samples with the replacement of a single random sample, allowing to obtain estimates of precision measures, as well as to perform hypothesis testing in situations where no information about the sampling distribution of a statistic is available or in cases where the sampling distribution is dependent on unknown parameters (Paule-Vianez, 2019; Garmendia, 2020; Crisóstomo, 2021). The data analysis was carried out using the bootstrap technique to determine the confidence intervals on the results of the experiment, the variables taken into consideration were: temperature, humidity, precipitation and number of drills per trap (Serrano-Gallardo et al. 2006; Lanteri, 2007).

Bootstrap estimation begins by obtaining an original sample of size n from which several bootstrap samples will be generated. These samples are created by re-sampling with replacement. For each of these bootstrap samples, the statistic of interest (such as mean, median, etc.) is calculated, repeating this process many times, usually thousands of times, to obtain a distribution of the calculated statistics (Ossa-Ossa, 2022; Narcisa, 2023).

The final estimate of the statistic of interest is obtained as the mean of all statistics calculated from the bootstrap samples. Furthermore, from this distribution, confidence intervals can be constructed by taking the appropriate percentages. This process made it possible to obtain estimates and confidence intervals without the need to assume a specific distribution for the original population (Sandoval, 2021; Alves, 2023)

Application of the model to determine the population dynamics of Coffee berry borer.

Four models were used to determine the best model to explain the population dynamics phenomenon under study: Weibull (Carmona-Londoño, 2023), Morgan (Solórzano-Thompson et al. 2021), Richards (Guera et al. 2019) and Multiple linear (Baños et al. 2019).

The models used were selected for their flexibility in modeling events such as pest survival and their reliability analysis (García et al. 2024). In population dynamics, the optimal model will be defined by its ability to adjust the shape of the growth curve through two key parameters: shape parameter and scale parameter, for simulation, analysis and optimization in processes related to agricultural management and in this case to Coffee berry borer control (Gonçalves, 2022).

With respect to the Weibull model Carmona-Londoño (2023) indicates that this model is especially valuable for its ability to fit different types of data observed in these areas such as precipitation, humidity, and temperature. Its flexibility comes from the shape parameter k, which allows the model to adapt to failure or mortality rates that may be decreasing, constant, or increasing over time. This makes it applicable not only to processes with simple behaviors, but also to those that change their behavior over time (Vargas-Sánchez, 2020).

The model selection was due to factor A and C, which corresponds to factor A relates to the precision or accuracy of the model, i.e., how well the model fits the observed data factor C, on the other hand, refers to the complexity of the model, which is measured in terms of the number of parameters used in the model, which is the ratio of the accuracy of the model, which refers to a metric for model selection and implies twice the accuracy minus twice the logarithm of the length of the model which implies a trade-off between how good the model is and how complicated the model is.

$$AIC = 2K - 2In(K)$$

With respect to the Richards model according to Guera et al. (2019) is particularly useful when the population growth rate is not expected to be constant, but to vary in a non-linear manner, showing distinct phases of accelerated and decelerated growth.

Multiple linear regression according to Baños et al. (2019) note that it is widely used in a variety of areas, including economics, biology, engineering, and social sciences, to identify and quantify relationships between multiple factors and a variable of interest.

According to (Solórzano-Thompson et al. 2021) Morgan's model is a tool used in the population dynamics of organisms, which helps to describe the growth behavior of a population under different conditions, unlike other models, it incorporates parameters that help to adjust the growth curve, it shows phases of rapid growth followed by stabilization, the application in population dynamics is relevant because it allows to foresee the future behavior of the pest.

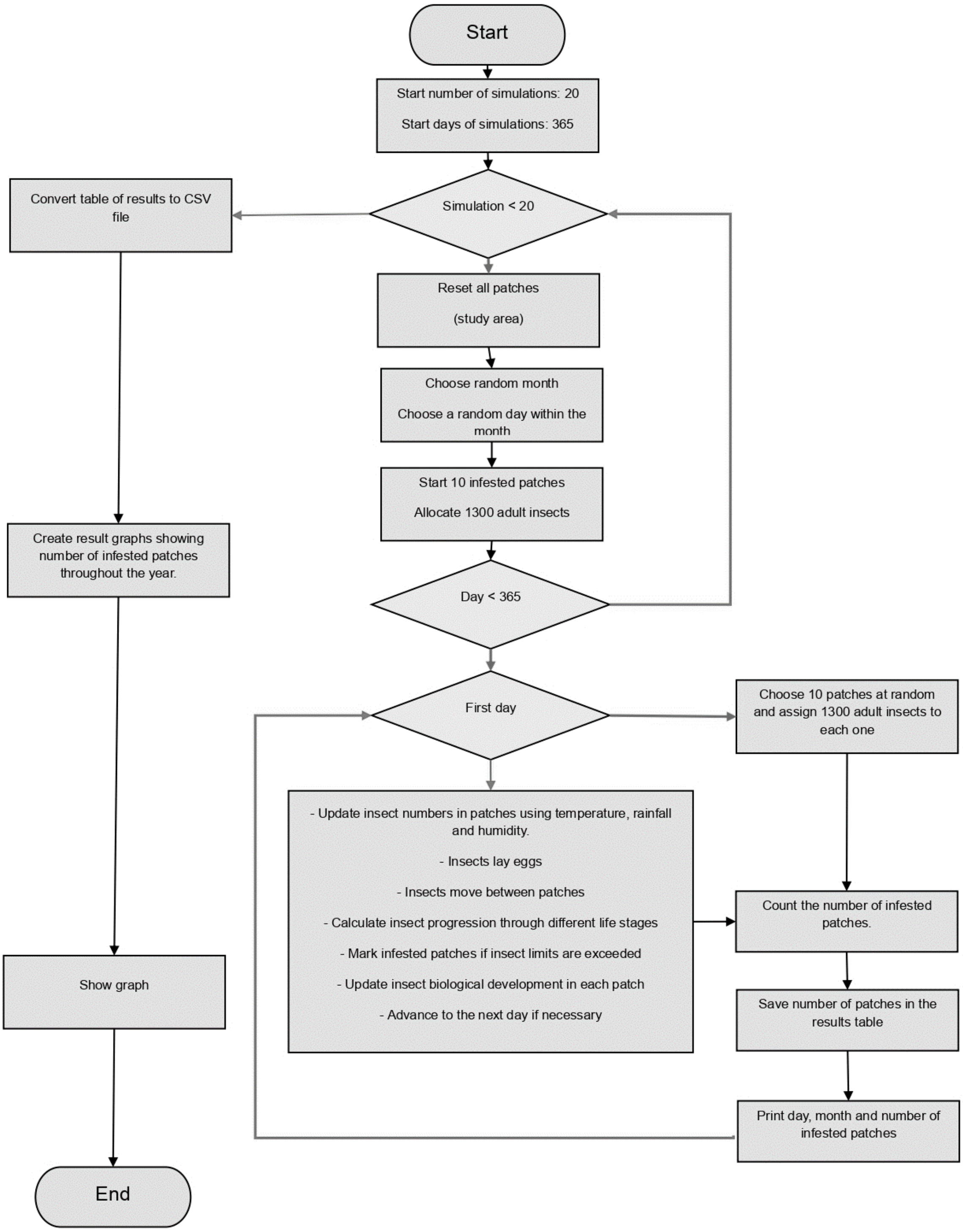

Figure 1. General outline of the theoretical and methodological design.

g) RESULTADOS

As a result of the coffee berry borer trapping activity, carried out from January to December 2023, it was obtained that of the total of 125 farms reviewed in the four study municipalities where the insect was present in all municipalities, Table 1 shows the total number of berry borers captured, which were 935, with an average of 1.79 berry borers per trap, with an average standard deviation of 1.74. 79 burs per trap, with a standard deviation of 1.74, the summarized data of the presence of the berry borer per trap and the environmental conditions of precipitation, temperature and humidity in a study, the captures vary from a minimum of 1 to a maximum of 18 burs. Regarding precipitation, an average of 55.24 mm was recorded, with a maximum of 462.9 mm and a standard deviation of 87.83 mm. Regarding temperature, it averaged 22.59 °C, with a minimum of 13.8 °C and a maximum of 29.9 °C. Finally, the total humidity was 33.30 %, with an average of 63.80 %, a minimum of 40 % and a maximum of 80 %. These data reflect the climatic variability and the response of the Coffee berry borer in the different conditions of the study.

Table 1. Coffee berry borer sampling data for the four municipalities (Amatepec, Sultepec, Tlatlaya y Tejupilco)

Unit of measure	CBB/trap	Precipitation	Temperature	Humidity
Average	1.79	55.24	22.59	63.80
Minimum	1.00	0.00	13.80	40.00
Maximum	18.00	462.90	29.90	80.00
Standard deviation	1.74	87.83	5.00	10.59
Sum	935.00			

The spatial distribution of Coffee berry borer is shown in Figure 2. Each mark on the map represents a sampling point, most of the marks are in the municipality of Amatepec (38 plots out of 125), standing out as the area with the highest infestation. Likewise, some scattered points can be observed towards the north and northeast of the State (Tejupilco), indicating the presence of the pest in these areas, although with a lower density. This information is crucial for both local authorities and farmers, as it allows the implementation of more effective control and prevention measures, focusing resources on the most affected areas and monitoring regions with an emerging presence of the pest. This geographic analysis provides a key tool for phytosanitary risk management, facilitating the design of strategies that minimize the spread of Coffee berry borer and optimize crop protection throughout the State of Mexico.

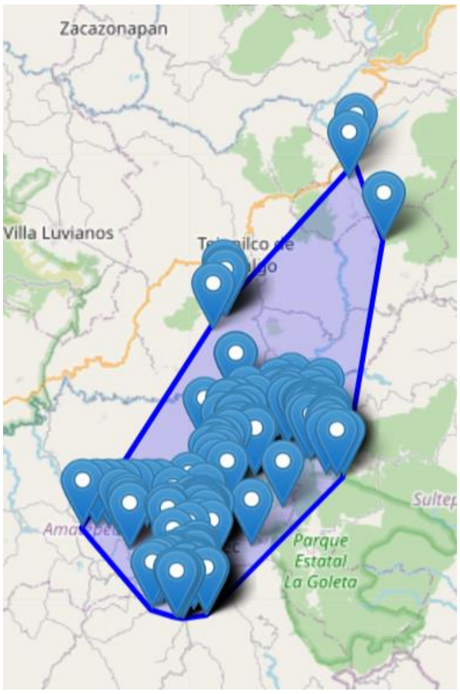

Figure 2. Location of Coffee berry borer in four municipalities (Amatepec, Sultepec, Tlatlaya and Tejupilco) State of Mexico.

Data Analysis

Normality of data.

To determine the reliability of the results obtained, the statistical error resulting from the Bootstrap median test was evaluated, since it has the capacity of the heuristic techniques implemented to solve the model (solutions close to or better than the known value) and the reliability. The Boostrap median test is a nonparametric technique that provides estimates of the statistical error in confidence intervals, imposing few restrictions on the random variables analyzed. (Santillán-Espinoza, 2022), Figure 3 shows the result of the Bootstrap estimation, which gave us the histograms obtained with the debugging of the data obtained with this conceptual and mathematical model, the graphs were obtained according to their states of evolution, such as the model of a single species, of two species without the age structure, of the matrix with the age structure and process oriented.

With this, the simulation of infestation behavior was run taking into account exogenous variables such as the environment, host and the pest, as well as endogenous variables such as the infestation itself and the fruits drilled by the borer.

In the simulation model, environmental conditions played a role in increasing mortality in each of the stages, resulting in a model to study infestation behavior that helps us to predict and understand how it spreads, as well as to see how it affects the crop in the long term.

The prediction model works with the geographical points, temperature, humidity, precipitation and the number of berry borers per trap that were found; in Figure 3, the histogram can be seen, which gives us the reference of the probability that a trap that was placed in a plot is checked, which means that of the total of the existing traps there is a probability that the insect is present, where it is represented from 80 to 82 % that if it is checked, the berry borer will be found.

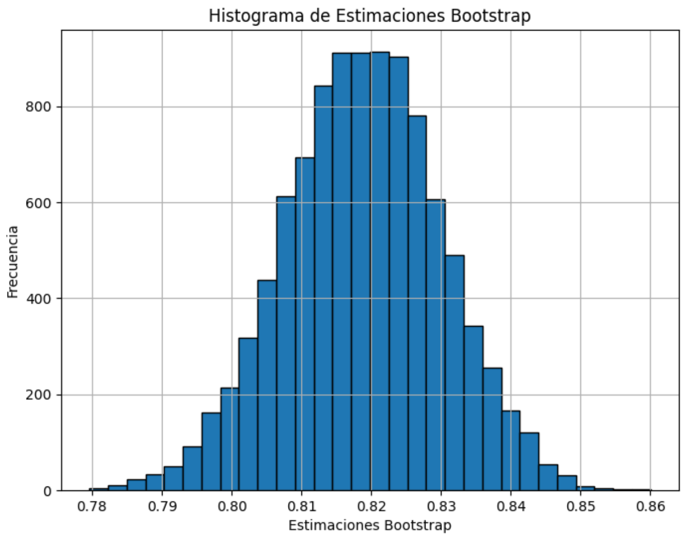

Figure 3. Histogram of Coffee berry borer presence in the traps.

On the other hand, Figure 3 indicates that the probability of the presence of the pest in any of its stages is from 20 to 24 %; the main comparison of the two histograms is that in one there is a probability of finding the Coffee berry borer consciously looking for it, which is 80 %, and 20 % that it already exists within the crop.

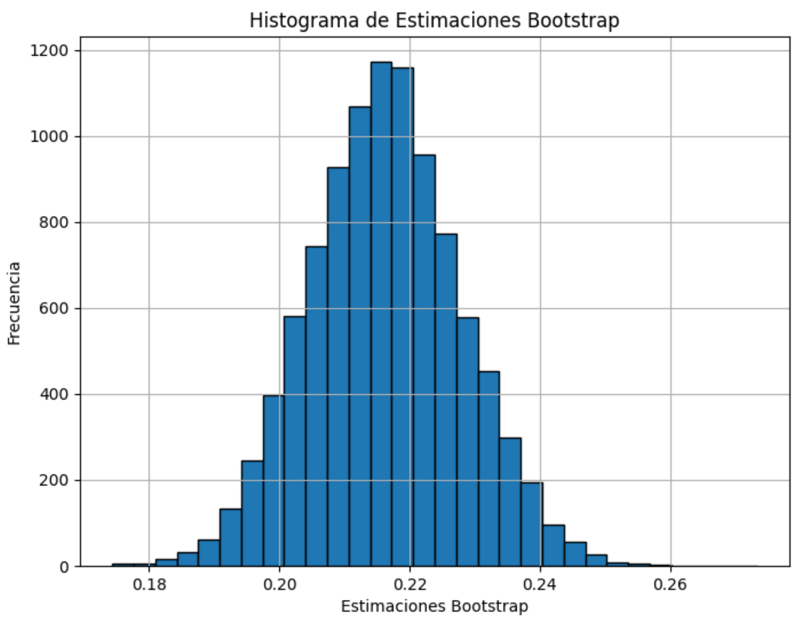

Figure 4. Presence of the coffee berry borer within the crop.

Application of the model, to determine the population dynamics of the Coffee berry borer

he simulation details the evolution of Coffee berry borer infestations and provides an in-depth view of how these insects can proliferate in a plantation throughout the year. This analysis considers several factors:

Climatological Factors: Temperature, humidity, and rainfall play crucial roles in the biology and behavior of the Coffee berry borer. Higher temperatures can accelerate the insect's life cycle, while changes in humidity can affect its development and survival (Olvera-Vargas, 2020)

Biological Factors: Includes the interaction between the Coffee berry borer and other organisms in the ecosystem, such as natural predators and competitors. These factors can influence the population density of the pest (Chuaire et al. 2024)

Behavioral Factors: The behavior of the Coffee berry borer, such as its tendency to migrate or stay in certain areas, is affected by the environment and climatic conditions. Simulations can show how these tendencies affect the spread of infestation (Bacca et al. 2021)

Life Cycles and Population Dynamics: The simulation also models the reproductive cycles of the coffee berry borer, allowing to predict at what times of the year population peaks are expected and how these peaks correlate with environmental conditions (Chuaire et al. 2024)

The simulation results provide several valuable tools for planning and managing Coffee berry borer infestation:

Risk Prediction: Simulation can identify periods of increased infestation risk by correlating climate data with Coffee berry borer biological cycles. This allows plantation managers to anticipate and prepare for critical times (Jiménez et al. 2022)

Evaluation of Strategies: Allows you to test the effectiveness of different management strategies before implementing them in the field. For example, insecticide treatments or cultural practices can be simulated to see how they affect pest spread.

Resource Optimization: By anticipating critical periods, resources (such as personnel, insecticides, and other control measures) can be allocated more efficiently, reducing costs and improving the effectiveness of pest control (Elizabeth, 2014).

Adaptation to Changing Conditions: The simulation can adapt to different climate and management scenarios, providing customized recommendations based on current and future conditions (Bacca et al. 2021).

Integral Vision: Allows for a more complete understanding of how various factors interact to influence infestation dynamics, rather than analyzing each factor in isolation (Olvera-Vargas, 2020).

More Accurate Predictions: Combining data of different types improves the accuracy of predictions and allows for a tighter, more effective response (Duran-Peralta, 2022).

Informed Decision Making: Facilitates decision making based on detailed, multidimensional analysis, improving the chances of successful infestation management (Lozano-Povis, 2023).

Continuous Update: Models can be continuously updated with new data, allowing for dynamic adjustments in management strategies as conditions change (Abbate, 2022).

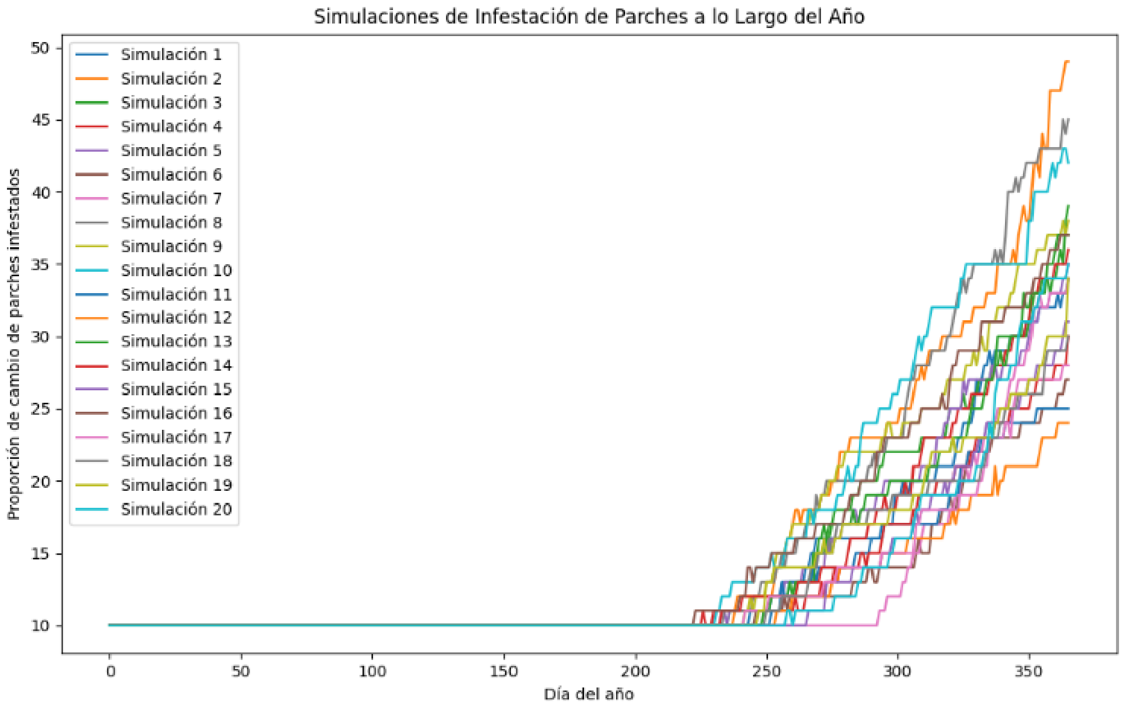

Figure 4. Simulation of the Weibull model

Figure 4 shows the graph that represents simulations of Coffee berry borer infestation in crop patches throughout the year where the variables of humidity, temperature, precipitation and borers per trap, in the graph the infestation remains stable until the 221st day of the year, when the proportion of infested patches begins to increase rapidly because the climatic and environmental conditions of the region favor a large growth of the pest.

The different lines represent different simulations, possibly with variations in the initial conditions of the variables showing that each combination affects the spread of the infestation. In practical terms, this information can help farmers and crop managers anticipate and control the spread of Coffee berry borer by adjusting management practices according to expected environmental conditions.

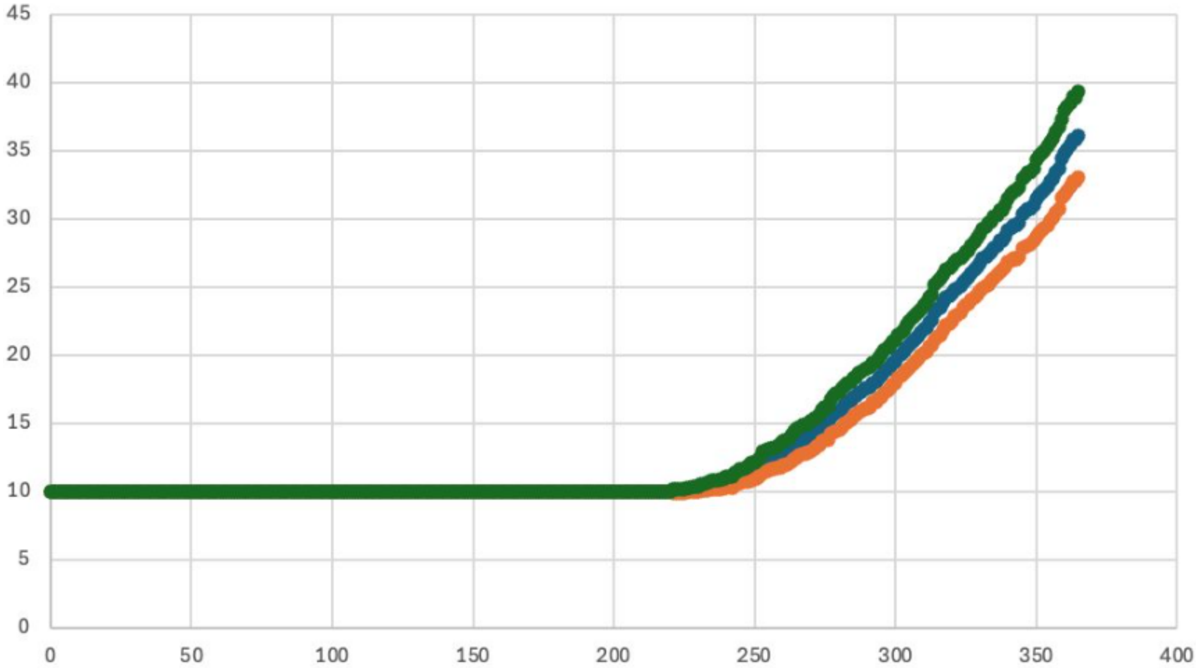

Figure 5. Extent and growth of the coffee berry borer simulation.

Figure 5 shows the growth rate of the insect and the amplitude of growth once the coffee berry borer is detected, it can be a slow growth but then it will increase, taking into account this, the growth should be observed from day 221 because 50 % of the plots of one hectare will be infested, also mention that below the bottom line the growth is linear and above the line itself the growth is exponential.

The selection was made based on the criteria of A and C. Table 2 shows the values where it is observed that the Weibull model is the one that generates the best positive value showing the growth of the pest in the period of one year of simulation showing that from day 221 is where an infestation begins with exponential growth as shown in Figure 5.

Table 2. Simulation statistics

U. of measurement	P	Var	E.Est.	L.Inf.	L.Sup.	Cab.	C.Inf.	C.Sup.
Average	13.89	6.11	0.30	13.30	14.49	0.004	0.003	0.004
Minimum	10.00	0.00	0.00	9.95	10.00	-0.005	-0.005	-0.004
Maximum	36.15	50.87	1.59	33.02	39.31	0.030	0.030	0.030

P: averageo; Var: variance; E.Est.: standard error; L.Inf.: lower limit; L.Sup.: upper limit; Cab: changes; C.Inf.; lower gear; C.Sup.: superior change.

Table 2 presents the statistical results that support the selection of the weibull model as the most efficient to describe the population dynamics of the Coffee berry borer, the values obtained show that the main parameter (P) has an average of 13.8, with a considerable variance and a confidence interval that goes from 13.30 to 14.49, the average standard error of 0.30 indicates the precision of the estimates, while the values related to the additional parameter range from -0.005 to 0.030, over the course of one year of simulation, the model predicts that the infestation starts exponentially around 221, which is represented graphically

DISCUTION

According to Perez-Constantino (2023) the presence of the coffee berry borer had not been reported in the State of Mexico until 2017, in the study indicates that two isolated cases were found in the region, According to Fachin et al. (2019) for the proliferation of the Coffee berry borer is linked to climatological factors such as wind, rain. Solar radiation, which reduce the capture of the progenitor females of this pest, in our study the results indicated that in all the farms there was presence of the Coffee berry borer in a greater or lesser percentage, it should be noted that the municipality with the highest number of farms was the municipality of Amatepec, likewise Constantino, et al. (2024) mentioned that temperature is therefore the variable that most favors the development of the coffee berry borer, increasing its reproductive rate and the number of generations per year, while Morocho-Vega (2022) indicated that climatic and behavioral factors influence the life cycle and population dynamics of the coffee berry borer.

In this study, the spatial distribution of the coffee berry borer was found in all the farms sampled. In the state of Mexico, this pest could be considered new since it was detected in 2017 (Pérez-Constantino, 2023).

according to (Santiago-Hernandez, 2023), indicates that the coffee berry borer uses migration as a method of survival, this was also observed by (Mesa et al. 2017), since it indicates that the pest is always on the move inside, increasing the growth of this pest (Constantino, 2021). It indicates that the number of coffee trees infested by the Coffee berry borer lasts almost throughout the entire harvest period, with the highest activity of Coffee berry borer flights and the highest infestation occurring during dry periods with greater sunlight.

With the comparison of the simulations, the interpretation of the population dynamics of the Coffee berry borer stands out, particularly in the last days of the year, where higher temperatures are observed. This coincides with the information provided by Constantino et al. (2021), who point out that climate, especially high temperatures, significantly influences the development and reproduction of the Coffee berry borer in the remaining coffee fruits, those that remain in the crops after harvest.

On the other hand, simulation analyses provide a valuable framework for understanding how Coffee berry borer affects the plantation throughout the annual cycle (Mora-Aguilera et al. 2021). These simulations not only allow the prevention of periods of increased risk of infestation but are also an indispensable tool to evaluate and optimize management strategies, better allocating resources according to changing climatic conditions. A key example is observed by Molina (2022), who shows in his simulations that Coffee berry borer infestation remains stable until the 250th day of the year, at which point it begins to increase, probably due to the appearance of favorable climatic conditions.

As mentioned, (Vargas-Sánchez et al. 2020) it involves estimating the parameters of the distributions by Bayesian Statistics simulation method, specifically the Gibbs sampler. This presented methodology will allow calculating performance measures of queuing systems when arrivals and service behave as a Weibull, even when they behave exponentially, since this is a particular case of the previous one.

The use of simulations in this context has provided valuable tools for farmers to anticipate and control the spread of the pest, adjusting their management practices according to the prevailing environmental conditions. This allows them to implement more precise and efficient interventions, minimizing the economic and environmental impact of Coffee berry borer.

In contrast to previous studies using other models, the results obtained with the Weibull model suggest that it provides a better representation of the phenomenon studied. The ability of the Weibull model to adapt to the dynamic temporal variables of the infestation is consistent with recent research, which has highlighted its flexibility in capturing events with fluctuating rates of occurrence over time. This reinforces the suitability of Weibull as a predictive tool in the study of Coffee berry borer population dynamics, standing out for its accuracy in estimating critical infestation periods and its applicability.

The Weibull model is characterized by its ability to describe systems that present variability in their patterns, as pointed out by Corzo & Bracho (2019). This makes it adaptable to diverse dynamics, which was used in this study on the population dynamics of the coffee berry borer. In particular, the model effectively captured population fluctuations, offering better fits compared to other models evaluated.

The analysis included the number of detections by epidemiological groups, as reported by OISA. According to Arreola-Martínez (n.d.), the calculation of the average, minimum, maximum and standard deviation of the variables made it possible to identify the type of distribution of the data and, consequently, to select the most appropriate statistical model. This approach was key to analyzing the patterns present in the data collected, thus ensuring that the model chosen will provide an accurate and reliable interpretation of the results. The appropriate selection of the model, in this case the Weibull model, was fundamental to effectively describe the behavior of the variables studied and to optimize the prediction of the population dynamics of the Coffee berry borer.

In the process of validation of the Weibull model, its remarkable ability to accurately describe the behavior of the Coffee berry borer is inspected. Montoya et al. (2022) report that the model has a minimum probability of 71 % relative error of less than 30 %, which supports its reliability, showing that it does not always overestimate the observed infestation.

Regarding the population dynamics of the insect, the model proposed by Bellows and Birley was adopted, which uses a set of equations to estimate the development of individuals over several cohorts or generations entering a state at different times. The application of this model requires knowledge about the statistical distribution of entry times to the first state; however, when this information is not available, a shape parameter can be assumed. This model includes two main expressions that facilitate this estimation.

For each of the conditions analyzed, the mean and standard error were calculated, performing a 5 % analysis of variance with the response variables under a design. Regarding the population behavior and control strategies of the Coffee berry borer during the retention of harvesting passes, it has been reported that the ants *Solenopsis picea* and *Crematogaster crinosa*.

Conclusions

The simulations carried out on the population dynamics of the coffee berry borer, together with the application of the Weibull model, proved to be effective tools for describing and predicting crop infestation. The ability of the environmental model to adapt to variations in conditions and provide accurate estimates, as shown by its minimum probability of relative error, highlights its usefulness in the management of this pest. Compared to other models evaluated, Weibull showed a better fit, capturing population fluctuations more accurately and allowing for more precise decision making.

In addition, the analysis of CBB generations, based on the Bellows and Birley model, complemented the understanding of the insect's dynamics, estimating its development over time. Although the application of this model requires detailed information on the temporal distribution of cohorts, its flexibility in assuming unknown parameters makes it a viable option when data are limited. These combined approaches allow a better identification of the periods of highest infestation risk and, therefore, a more efficient management of the pest throughout the agricultural cycle.

Finally, biological control strategies also play a crucial role in Coffee berry borer mitigation, as observed with the action of the ants *Solenopsis picea* and *Crematogaster crinosa*, which significantly reduced infestation on coffee branches. However, the absence of these species in certain regions, such as the State of Mexico, underlines the need to explore control approaches adapted to local conditions. The integration of predictive models, such as Weibull, with biological control methods and optimized agricultural practices, constitutes a promising avenue for sustainable Coffee berry borer control.

AUTHORS' CONTRIBUTION

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