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Environmental and geophysical variables as indicators of the potential distribution of *Dalbulus maidis* (Hemiptera: Cicadellidae) in Huila, Colombia

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Abstract:

Dalbulus maidis is a pest of great importance for corn in America and Colombia, due to its potential for transmitting pathogens that cause plant diseases and result in large crop losses. Environmental conditions are considered among the main factors in the geographic distribution of pests. **Objective:** To identify the climatic and geophysical elements that affect the presence of *D. maidis* and its potential geographic distribution in Huila (Colombia) using the MaxEnt algorithm in order to determine the risk of presence of this species in the area. **Scope:** to provide elements to phytosanitary and environmental authorities, researchers and agricultural extensionist agents in management strategies for this pest in corn-producing regions. **Methodology:** A total of 29 environmental variables were considered. Sixty-three models were fitted and evaluated using goodness-of-fit metric and the area under curve (AUC) adjustment, and the contribution of the variables was evaluated using the jackknife analysis. **Main results:** The resulting habitat suitability model was fitted with an AUC value of 0.82, being the topographic diversity index, the annual average temperature, reference evapotranspiration, precipitation of the driest month, annual precipitation, and wind speed the most important variables for predicting habitat suitability of *D. maidis*. **Conclusion:** 62.49 % of the study area was classified as high and medium-high habitat suitability, 29.98 % as medium, and only 7.53 % as low and medium-low.

Keywords: MaxEnt, habitat suitability, climate variables, biophysical variables, presence, management, insect pest.

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Variables ambientales y geofísicas como indicadores del potencial de distribución de *Dalbulus maidis* (Hemiptera: Cicadellidae) en Huila, Colombia

Resumen:

Dalbulus maidis es una plaga de gran importancia para el maíz en América y Colombia, debido a su potencial de transmisión de patógenos que generan enfermedades en las plantas causando grandes pérdidas del cultivo. Entre los factores principales en la distribución geográfica de las plagas se consideran las condiciones ambientales. **Objetivo:** identificar los elementos climáticos y biofísicos que inciden en la presencia de *D. maidis* y su distribución geográfica potencial en el Huila (Colombia) utilizando el algoritmo MaxEnt, con el fin de conocer el riesgo de presencia de esta especie en la zona. **Alcance:** proporcionar elementos a las autoridades fitosanitarias, ambientales, investigadores y extensionistas agropecuarios en estrategias de manejo de esta plaga en las regiones productoras de maíz. **Metodología:** Se consideraron 29 variables ambientales. Se ajustaron 63 modelos que fueron evaluados mediante la métrica de bondad y ajuste de área bajo la curva (AUC) y se evaluó la contribución de las variables a partir del análisis de Jackknife. **Principales resultados:** El modelo de idoneidad del hábitat resultante fue ajustado con un valor de AUC de 0,82, siendo el índice de diversidad topográfica, la temperatura media anual, la evapotranspiración de referencia, la precipitación del mes más seco, la precipitación anual y la velocidad el viento las variables de importancia en la predicción de la idoneidad del hábitat de *D. maidis*. **Conclusión:** El 62,49 % del área de estudio se clasificó como zonas con alta y media alta idoneidad del hábitat, el 29,98 % como media y solo el 7,53 % como baja y media baja.

Palabras claves: MaxEnt, idoneidad del hábitat, variables climáticas, variables biofísicas, presencia, manejo, insecto plaga.

Introduction

Corn is one of the main agricultural products in the world and of great economic importance for America and Colombia. However, this crop is exposed to the pressure of multiple pests and diseases. Currently, its production in America faces a major threat from the insect *Dalbulus maidis* (*D. maidis*) (De Long and Wolcott, 1923) (Hemiptera: Cicadellidae) (Figure 1), commonly known as the corn leafhopper, which has become a significant pest in corn-producing areas, mainly due to its ability to transmit phytopathogens. It is the primary vector of maize bushy stunt phytoplasma (MBSP), corn stunt *spiroplasma* (*Spiroplasma kunkelii*) (CSS), and maize fine streak virus (MFSV). The transmission of these pathogens is persistent and propagative, which may result in high infestation and yield losses of up to 90% (Dietzgen *et al.*, 2016; Santana *et al.*, 2018; Foresti *et al.,* 2022).

Figura 1. *Dalbulus maidis.* (De Long and Wolcott, 1923) (Hemiptera: Cicadellidae. Photograph taken by Buenaventura Monje Andrade.

Huila is one of the corn-producing Departments in Colombia with a production of 28,072 ton and 11,413 ton in technical and traditional corn, respectively (MADR, 2021). On the other hand, Huila is the corn pantry of other Departments such as Caquetá and Putumayo. An increase in different pests and diseases has been detected in recent years, including leafhoppers, which has represented a marked decrease in yield or migration to other production systems. In 2016, during the seasons of low precipitation and high temperatures, producers from the Municipalities of Campoalegre and Palermo reported an increase in leafhopper populations, severe plant damage, and reductions in corn yield. The Colombian Agricultural Institute (ICA, for its acronym in Spanish) indicated that these losses were associated with the MBSP disease, which was detected in symptomatic plants and individuals of *D. maidis* (ICA, 2016). The Municipalities of Aipe and Garzón were later reported as affected, and the problem continues because it has also been found in the Department of Tolima (González, 2019).

The development and reproduction of insects and pathogens are strongly influenced by climatic conditions, making them key factors driving the specific distribution of pests in agroecosystems, as well as the severity of their infestation. Therefore, identifying environmental constraints that impact the geographic distribution and abundance of pest insects is crucial for effective management, particularly in the case of invasive species (Wang *et al.*, 2009; Gutierrez *et al.*, 2011; Sánchez Reinoso, 2021). Among the important climatic factors in the development of *D. maidis* is the temperature, and populations are known to increase in dry and warm seasons (Varón and Sarria, 2007). Van Nieuwenhove *et al.* (2016) evaluated the effect of different temperatures on the development, performance, and fitness of *D. maidis*, finding that temperature had a significant influence. However, the range of vector distribution may be limited mainly by the availability of the host plant. On the other hand, Santana *et al.* (2019) conducted a study to identify suitable areas for *D. maidis* worldwide from the WorldClim dataset at a 2.5 min (~5 km) resolution for the period from 1950 to 2001 and to predict the effects of climate change in 2050 and 2070 under the RCP4.5 and RCP8.5 scenarios using the MaxEnt algorithm. They found that the corn leafhopper prefers areas with higher winter temperatures, moderate to low annual temperatures, and distinct wet and dry seasons and that, for South America, climate change will reduce the suitable areas for the pest, especially in Brazil. It should be noted that only climatic suitability was considered in this study, and other factors may favor or limit the distribution of this species at present and in the future.

Considering the relationship between climate and the biological processes of insects, little information is available on *D. maidis* (Foresti *et al.*, 2022). Since this is a problem for corn producers, specifically in Huila, it is crucial to study the relationship of *D. maidis* with the climatic and environmental conditions at a regional level in such a way that information can be obtained for better management of the territory according to the risk of occurrence of this species in the area. Therefore, this work aims to determine the potential geographic distribution of *D. maidis* in Huila and identify the environmental and geophysical factors that influence its presence by implementing the MaxEnt, maximum entropy algorithm, including local and updated climate information, geophysical variables, and sampling data for *D. maidis* in the Department.

Materials and Methods

Study area

The study area is Huila (Colombia), located between 1°33’08” and 3°47’32” north latitude and 74°28’34” and 74°28’34” west longitude (Figure 1). Cobos *et al.* (2018) recommend delimitating the modeling surface (background) so as not to affect the analysis, parameterization, validation, and comparisons of the model. Therefore, the calibration area for the studied species was delimited between 12 and 36 °C of mean temperature (Tm) following the habitat suitability criteria of Merow *et al.* (2013) and the study by Van Nieuwenhove *et al.* (2016), which address the suitable temperatures for the development of *D. maidis*. The Tm series were collected from meteorological stations in the Department, the multi-annual mean temperature was calculated for the period from 1985 to 2018, and interpolation was carried out using the R software (R Core Team, 2021). Finally, pixels outside the established temperature range were excluded, leaving only the green area observed (Figure 1).

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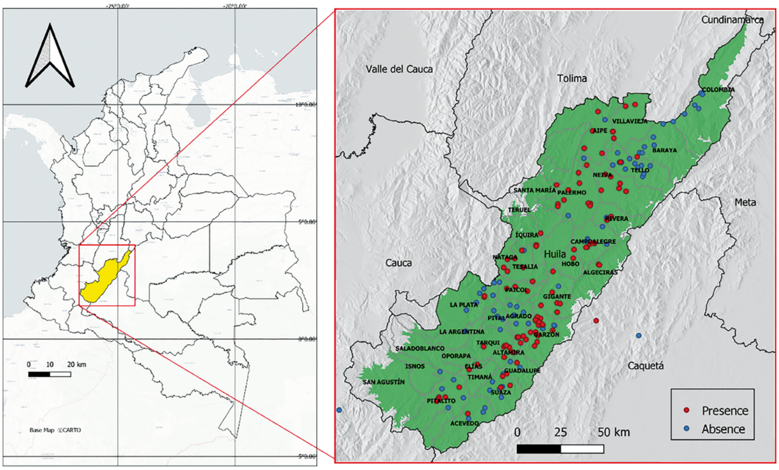

Figura 2. Study area and modeling (background) to determine the spatial distribution of Dalbulus maidis in the Department of Huila. Source: Own elaboration.

Collection of data on the presence of D. maidis

Initial data on the occurrence of *D. maidis* were obtained from records obtained through previous Agrosavia projects: *"Integrated management of phytosanitary alternatives for pests and diseases, for rice-corn-cotton systems in the inter-Andean valleys and the Caribbean"* ("*Manejo integrado de alternativas fitosanitarias en plagas y enfermedades, para los sistemas arroz-maíz-algodón en los valles interandinos y el Caribe*") phase I and II financed by the Ministry of Agriculture and Rural Development and carried out between 2018 to 2021, as well as monitoring information provided by ICA for 2020 and 2021 (ICA, 2021). Area sampling was designed per area to complete the records in municipalities or zones where the presence or absence of the species (incidence) was not reported. The points were randomly distributed within the modeling area, including zones with different biophysical conditions, without overlapping.

The established sampling was carried out between February and August 2022 in productive corn plots at any phenological stage or in weeds associated with the crop. When a sampling point was identified, a 10 m linear transect was carried out, involving two passes with an entomological net (Virla *et al.*, 2003). The insects were captured in 50 mL Falcon tubes with 70% ethanol. Each sample was georeferenced and coded with the point number, initials of the Municipality, and sampling date.

The collected samples were transferred to the Nataima entomology laboratory of the Agrosavia research center, where cleaning and prior classification by morphotypes were carried out. The species level was confirmed through the higher taxonomic order Hemiptera, family Cicadellidae up to species. Four taxonomic keys of the group were used, which include characteristics such as body color, eyespot, first posterior tarsomere, antennal flagellum, and distal anterior cells (Triplehorn and Nault, 1985; Knight and Webb, 1993; Triplehorn and Johnson, 2005; Sánchez-Reinoso *et al.*, 2021). In this way, the presence/absence of the insect was determined for each sample.

Subsequently, the presence records were adjusted and filtered by applying some of the criteria suggested by Cobos *et al.* (2018), such as removing repeated observations, removing records without decimal precision, correcting changes in latitude and longitude, in the sign of geographic coordinates and records outside the region of interest, unifying the coordinate system and removing null cells records. Information was obtained from 235 points, finding 136 presences of *D. maidis*. Upon applying the debugging filters, 106 points were selected for the modeling.

Predictor variables

Twenty-nine predictor variables were considered (Table 1), including 19 bioclimatic variables, which have been shown to directly influence the distribution of species (Jarnevich *et al.,* 2015), for example, in Trethowan *et al.* (2011). They have also been adopted in habitat suitability modeling studies for *D. maidis*, as in Santana *et al.* (2019). The bioclimatic variable layers were obtained through different interpolation methods using the R software (R Core Team, 2021) in climate series from 1985 to 2018 from meteorological stations located in the Department which are operated by the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM, for its acronym in Spanish). Raw data were downloaded through the DHIME website (IDEAM, 2022) and submitted to data quality and homogenization processes using the R package 'Climatol' (Guijarro, 2022).

Table 1. List of predictor variables.

Abbreviation	Variable
BIO1	Average annual temperature (°C)
BIO2	Average daily range
BIO3	Isothermality (BIO2 / BIO7) (*100)
BIO4	Temperature seasonality (standard deviation * 100)
BIO5	Warmest month maximum temperature of the (°C)
BIO6	Coldest month minimum temperature (°C)
BIO7	Annual temperature range (BIO5-BIO6) (°C)

BIO8	Mean temperature of the wettest quarter (°C)
BIO9	Mean temperature of the driest quarter (°C)
BIO10	Mean temperature of the warmest quarter's (°C)
BIO11	Mean temperature of the coldest quarter (°C)
BIO12	Annual rainfall (mm)
BIO13	Precipitation of the wettest month (mm)
BIO14	Precipitation of the driest month (mm)
BIO15	Seasonality of precipitation (coefficient of variation)
BIO16	Precipitaion in the wettest quarter (mm)
BIO17	Precipitation in the driest quarter (mm)
BIO18	Precipitation in the warmest quarter (mm)
BIO19	Precipitation in the coldest quarter (mm)
HR_annual	Annual relative humidity (%)
BS_annual	Annual sunshine (h)
Vv_annual	Annual wind speed (ms-1)
Dir_annual	Annual wind direction
ETo_annual	Annual reference evapotranspiration (mmd-1)
DEM_250	Elevation (m)
ACTOP	Landforms
GSTD	Topographic diversity index
CHILI	Continuous thermal insulation index
Coverage	Coverage

Source: Own elaboration.

According to the availability of georeferenced information in the study area and considering the possible influence of other climatic variables for the species, relative humidity and sunshine information from meteorological stations in the same period was incorporated and interpolated. The annual wind speed and direction layers supplied by IDEAM were included in the Colombian wind atlas (Ruíz *et al.,* 2017). The Rural Agricultural Planning Unit (UPRA, for its acronym in Spanish) and IDEAM provided the crop evapotranspiration layer (ETo) reference according to their study results (IDEAM and UPRA, 2022).

Landscape features such as elevation (derived from the digital elevation model provided by Jarvis *et al.* (2008), landforms, topographic diversity, and the continuous thermal insulation index from Theobald *et al.* (2015) dataset, which was obtained through the Google Earth Engine (GEE) platform (Gorelick *et al.,* 2017), were also included. The coverage layer was obtained from the Esri Inc. image server (ESRI, 2022). All layers were worked at a resolution of 250x250 m.

Modeling the potential distribution of *D. maidis*

Before the modeling, a collinearity analysis of the predictors was carried out since these should not be highly correlated. A cluster analysis using Euclidean distance and the full-linkage method was used to discard variables that presented redundancy. The variance inflation factor (VIF) was also used to eliminate variables with values greater than five, considered evidence of collinearity (Heiberger and Holland, 2015).

The maximum entropy method was used through the MaxEnt algorithm (Phillips *et al.,* 2017; Simões *et al.,* 2020) for the modeling, considering different configurations. The final predictors were combined, with nine values of regularization multipliers (RM) (0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5) and seven combinations of five feature classes (linear = L, quadratic = Q, linear-quadratic = LQ, linear-quadratic-product = LQP, linear-quadratic-hinge = LQH, linear-quadratic-hinge-product = LQHP, and linear-quadratic-hinge-product-threshold = LQHPT).

The output format of the model in this study was RAW, as only presences were assumed. Without strict absence data, the prevalence (probability of presence assuming a random sample design such that the locations of presence have a probability of plus or minus 0.5) cannot be distinguished (Phillips *et al.,* 2017; Ruiz de Larramendi, 2017; Simões *et al.*, 2020). RAW represents the likelihood or probability of Relative Occurrence Rate (ROR) as an estimate of the relative suitability of one location versus another, where the sum of the values in all cells equals one. Therefore, the interpretations of MaxEnt's predictions are an index of habitat suitability.

Response curves were generated to illustrate the variation in species ROR within the range of each variable. These curves were then analyzed for each predictor to obtain information on the ranges that are approximately suitable for the species according to the model.

Assessment of model performance

The ROC (Relative Operating Characteristic) curve and its corresponding goodness and fit metric AUC (area under the curve) were implemented for this study. AUC values can be between 0.5 and 1.0. A value of 0.5 means that the model has no discriminant value (equivalent to random classification). A value of 1.0 indicates that the model has separated presences from absences with a perfect fit, without errors. For example, an AUC of 0.74 means that the model will give a higher suitability value to presences 74% of the time. However, in the case of presences only, the value will always be less than one because there will always be random points in the ideal habitat.

The performance testing of the candidate models was carried out based on the AUC, with 500 iterations, separating 60% of the presence data for model training and 40% for testing with ten replicates using the Bootstrap technique. Another criterion for selecting the model is its degree of complexity, explained by the response curves. Models should have simple curves to be easily interpreted and avoid overfitting, allowing an accurate analysis of the main environmental drivers by identifying specific ranges for the species (Merow *et al.,* 2013). Therefore, the model was discarded if the response curves had a complex trace.

Final model and post-processing

The model was generated by selecting the best combination of features and RM parameters, combining the same regularization values but with the classes that lead to the most direct interpretation models. However, before selecting it as the last model, the predictors that provided less gain were discarded in order to choose those environmental variables with more information, excluding the variables with an AUC less than 0.6 in the jackknife results based on the study of Ruiz de Larramendi (2017). Based on this test, the final model was selected and adjusted.

Processing the final distribution map

The potential distribution map information based on the RAW output generated by MaxEnt is continuous and includes shallow values (close to zero) that are difficult to interpret. Therefore, it must undergo a reclassification of its values by first linearizing them through a natural logarithmic transformation and then a second reclassification to values from 0 to 1 (Romero Fernández, 2020). For this study, the model species distribution map was transformed and reclassified into five categories, whose values represent the habitat suitability of the species according to Table 2.

Table 2. Habitat suitability categories from the transformed ROR.

Transform ROR (MaxEnt)	Class	Habitat suitability
<=0.2	1	Very low
0.2–0.4	2	Low
0.4–0.6	3	Medium
–0.8	4	High
>0.8	5	Very high

Results

Predictor variables

Based on the cluster analysis, the 29 climatic and biophysical variables initially considered were grouped into 12 groups, from which 15 predictors were selected, including Vv_annual, BS_annual, HR_annual, GSTD, BIO12, ETo_annual, BIO2, BIO4, BIO1, BIO15, BIO17, ACTOP, Dir_annual, BIO16, and Coverage. Subsequently, BIO4 and BIO2 with IVF values greater than five were excluded.

Model testing

With the selected variables, 63 potential distribution models were calibrated and fitted using different combinations between classes and regularizations, which were evaluated based on the criterion of better AUC and lower complexity. In general, the models have a similar performance with AUC values between 0.822 and 0.852, except for the L class and the LQHPT combination, which show poor performance, especially the linear one (Figure 2). The best AUC results are obtained in the LQH models. Moreover, their response curves represent complex functions (over-fitting curves without clearly defined ranges and with abrupt changes in values).

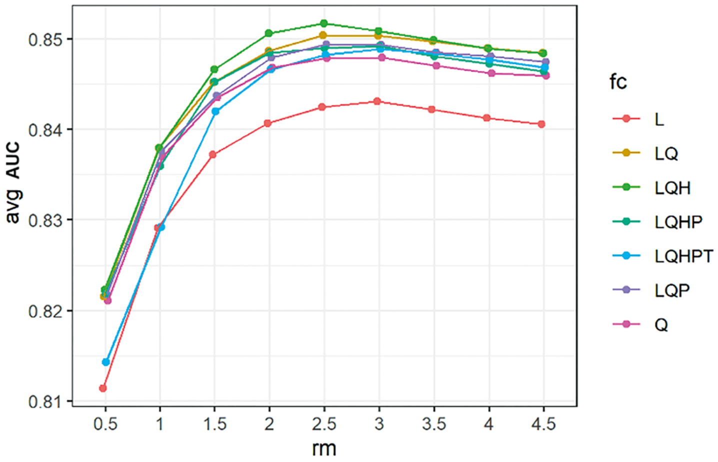

Figure 3. Test results of the 63 models. Source: Own elaboration.1

After selecting the LQP model with a 2.5 regularization, the jackknife was carried out and reviewed, discarding the variables BIO15, BIO16, relative humidity, sunshine, wind direction, landforms, and coverage, which presented AUC less than 0.6. Finally, the LQP 2.5 configuration was fitted again with the remaining variables, obtaining a model with AUC of 0.82, which is the result of the 10 replicates obtained from Bootstrap. The number of samples used training and testing the model, were 64 and 42, respectively, due to the proportion established in the 60–40% methodology.

Environmental factors that affect the potential distribution of *D. maidis*

Of the 29 variables initially considered, BIO1 (AUC=0.7315), BIO12 (AUC=0.6239), BIO17 (AUC=0.6535), ETo_annual (AUC=0.6921), GSTD (AUC=0.7759), and Vv_annual (AUC=0.6056) were the most important in determining the potential distribution of *D. maidis* (Figure 3).

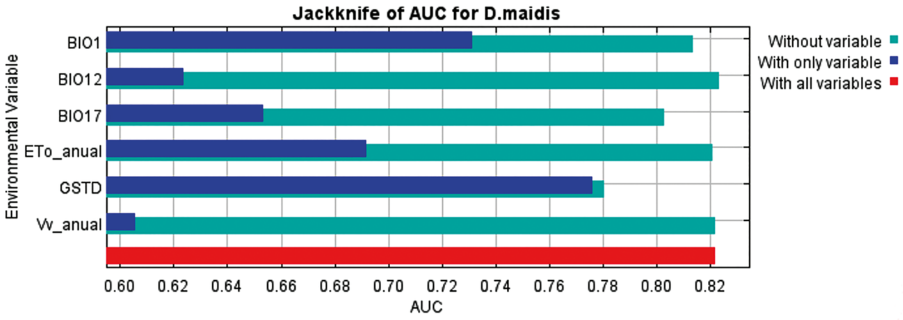

Figure 4. Final result of the jackknife model (LQP 2.5) for *D. maidis.* Source: Own elaboration.

To analyze the influence of the predictors on the potential geographic distribution of *D. maidis*, the response curves of the predictors considered in the model are presented in Figure 4. These represent the relationship between variables and relative occurrence rate (ROR), interpreted as the habitat suitability of the species. With them, it can be identified how the predicted ROR changes in a range of values for each predictor, showing the biological tolerances and habitat preferences of the species. Based on the response curves of *D. maidis*, the ROR increases with the increase in the mean annual temperature (BIO1) (Figure 4A) and reference evapotranspiration (ETo_annual) (Figure 4D), showing a significant increase in suitability from 24 to 28 °C and from 1,450 to 1,900 mm, which represent the warmest dry and very dry areas of the department. Meanwhile, ROR decreases with the increase in annual precipitation (BIO12), precipitation in the driest quarter (BIO17), GSTD, and wind speed (Vv_annual). Thus, the habitat suitability increases significantly below 1,450 mm for BIO12 (Figure 4B) and for values less than 300 mm for BIO17 (Figure 4C). It suggests again the preference of *D. maidis* for the driest areas and seasons, which for the province corresponds to the July-August-September quarter (BIO17). Wind implies that speeds lower than 3.5 m s-1 increase the ROR (Figure 4F), which is related to higher wind values not allowing *D. maidis* to settle. Therefore, its presence is optimized in less windy areas.

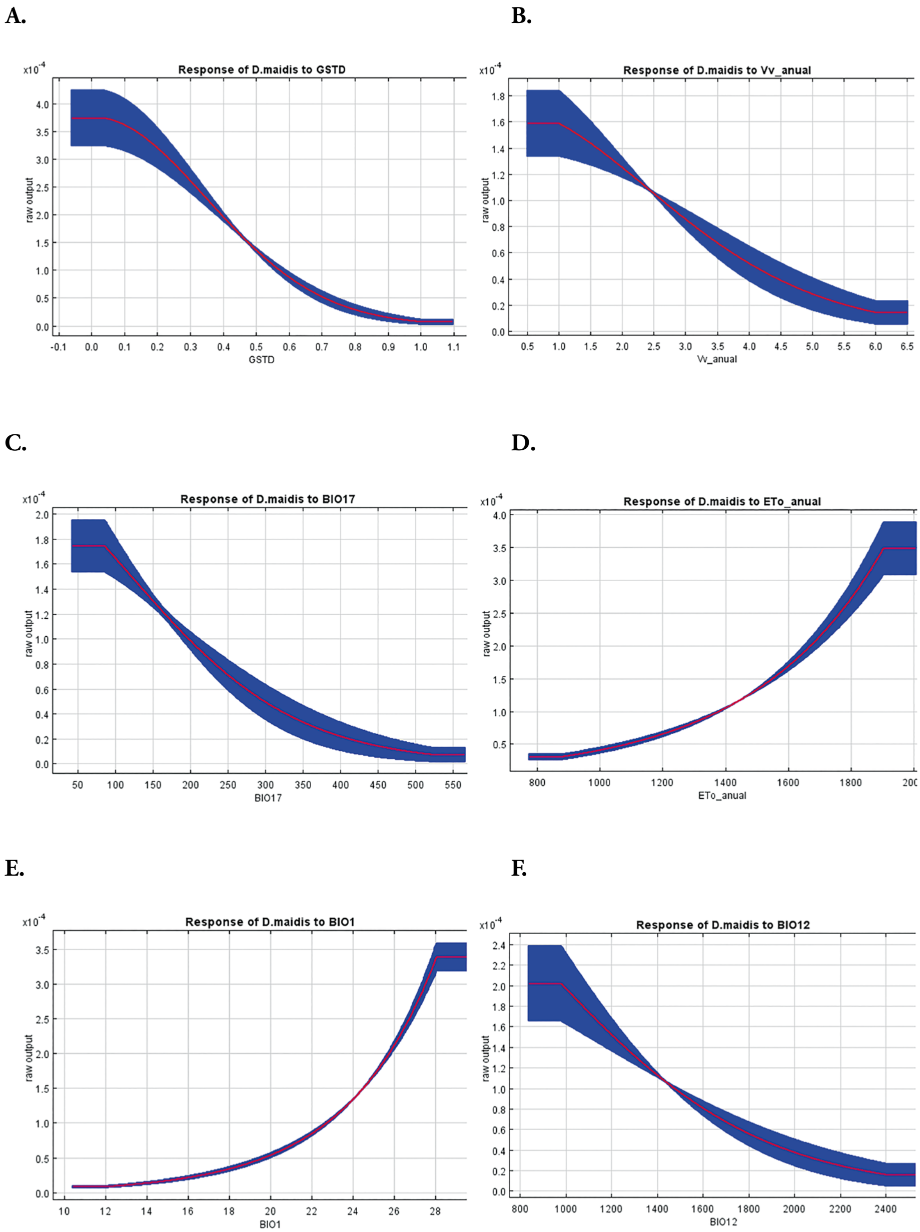

Figure 5. Relative occurrence rate (ROR) response curves of *D. maidis* concerning the model predictor variables: (A) BIO1 (B) BIO12 (C) BIO17 (D) ETo_annual (E) GSTD, and (F) Vv_annual.
Source: Own elaboration.

Potential distribution of *D. maidis* in the study area

Figure 5 shows the habitat suitability map of *D. maidis* in the study area, representing the potential distribution of the species in this region. It is noteworthy that a large part of the study area is classified with high and medium-high favorable environmental conditions for the occurrence of the species, being these categories 62.49 % (Table 3) of the total area. The most favorable areas (High), corresponding to 29.62 %, are located mainly in the Municipalities of Villavieja, Aipe, Tello, Neiva, Palermo, Rivera, Campoalegre, Yaguará, Hobo, Nátaga, Tesalia, Gigante, Paicol, La Plata, Agrado, Garzón, Altamira, Tarqui, Elías, Timana, Isnos, Suaza, and Guadalupe in the upper Magdalena river valley and to a lesser extent in Baraya, Algeciras, Argentina, Oporapa, Saladoblanco, San Agustín, and Acevedo. The medium suitability classification occupies 29.98% of the areas located towards the coldest areas of the province, and only 7.53% are categorized with low and medium-low suitability in the highest parts of the region (Figure 5, Table 3).

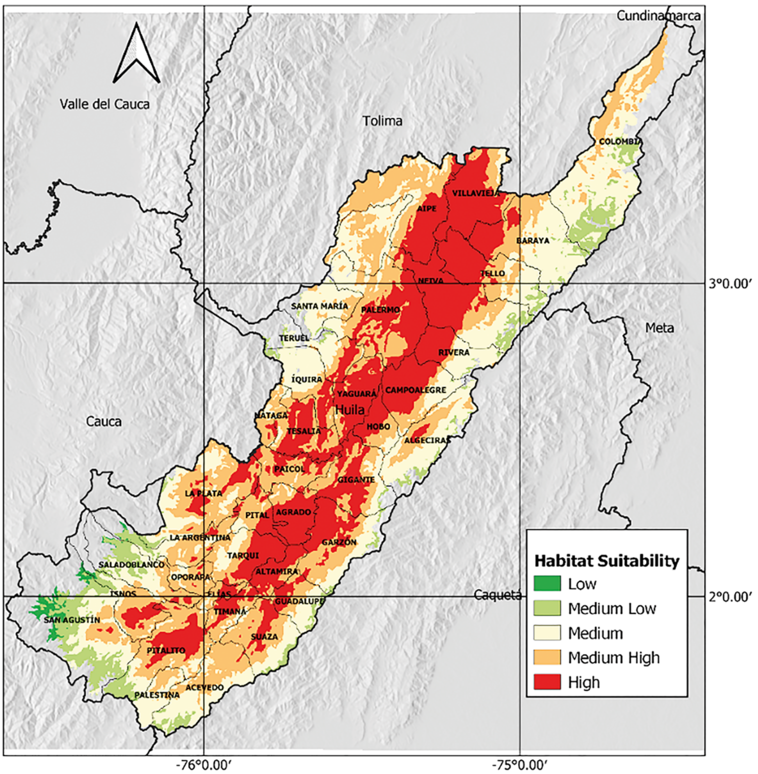

Figure 6. Habitat suitability map for *D. maidis* in the study area.

Tabla 3. Habitat Suitability percentages of D. maidis classified in the five categories.

Category	Area (ha)	Area (%)
Low	10012.5	0.62
Medium-low	112375	6.91
Medium	487837.5	29.98
Medium-high	534800	32.87
High	481937.5	29.62
Total	1626962.5	100

Discussion

D. maidis has been reported as one of the most important pests in Latin America (De Oliveira *et al.,* 2014). In Colombia, specifically in the Department of Huila, it has been notified as a vector of the pathogens that cause corn stunt complex disease and four morphotypes have been identified according to morphological characters that include total length, head length, and distance between the eyes (Sánchez-Reinoso *et al.,* 2021). Phytosanitary authorities have established specific planting dates for corn cultivation because of the increased presence of the corn stunt disease transmitted by *D. maidis* (ICA, 2023). However, there is a scarcity of scientific research on the natural history and focus on the optimal environmental conditions of this insect (Sanchéz-Reinoso *et al.,* 2021). Although a study of suitable habitat for the species has been reported worldwide (Santana *et al.,* 2019), the spatial resolution is not specific to regions where insect pests, weed species, phytoplasma and spiroplasma responsible for this severe disease have coevolved, resulting in yield losses of maize crops (Bendendo and Lopes, 2019; Jurga and Zwolińska, 2020). In addition, other climate variables derived from data from climate stations in the area with more recent information compared to databases commonly used in global studies like Worldclim dataset, were considered this study.

Since this study focuses on the characterization of the niche and the importance of environmental factors (predictors) in its distribution, models must have curves simple enough to be easily interpreted (Merow *et al.*, 2013) (Figure 3). The BIO1 and BIO12 corresponding to the average annual temperature and annual rainfall in this model coincide with the variables with the most significant contribution to predict the global distribution of *D. maidis* and the importance of the driest periods precipitation identified in the global study by Santana *et al.* (2019). They found BIO14 (precipitation of the driest month) an essential variable. This model includes BIO17 (precipitation in the driest quarter), which can also be related to the results of Foresti *et al.* (2022), revealing a positive correlation between air temperature and the population of *D. maidis* and a negative effect with rain. At the field scale, García da Cunha *et al.* (2023) reported that total precipitation, minimum temperature, relative humidity, and wind speed were the factors that significantly influenced the global distribution of *D. maidis*. The distribution of vectors and diseases influenced the behavior of the vectors and disease distribution. Furthermore, as this study did not only include climatic variables, the variable that contributes the most to the performance of the model presented in it is the topographic diversity index (GSTD), followed by average of annual temperature (BIO1), reference evapotranspiration (ETo_annual), BIO17, BIO12, and wind speed (Vv_annual), according to the jackknife result (Figure 4).

The topographic diversity index (GSTD) refers to the variable with the most significant contribution to the performance of the model. It represents the variety of temperature and humidity conditions available to the species as local habitats. This index expresses that a greater variety of topoclimatic niches should support greater diversity (Theobald *et al.*, 2015). Therefore, GSTD values less than 0.5 (lower condition for host species diversity) increase the habitat suitability of *D. maidis* (Figure 5E), that is areas with less competition or natural enemies for the insect that favor its settlement. The life history and variation of its populations has been related to the action of natural enemies and environmental factors (Liebhold *et al.,* 2018; Tórres-Moreno and Moya-Rayzoga, 2021; García de Cunha *et al.,* 2023). Promoting practices that have less impact on species diversity, such as *i*) the use of entomopathogenic fungi which use, unlike chemical insecticides, represents an alternative for the reduction of *D. maidis* populations; *ii*) crop rotation because only corn can have the damage caused for the pathogens; *iii*) an appropriate cultural control method has been recommended considering the bioecology of the pathogens; *iv*) the application of insecticides following the recommendations, especially during the early stages of cultivation; and, *v*) use of technologies capable of determining the infectivity rate of *D. maidis* populations using phytoplasma and/or by Spiroplasma. These may be some alternatives for reduction of *D. maidis* populations (Alves, 2020; Foresti *et al.,* 2022; Oliveira and Frizzas, 2022).

This study is one of the recent initiatives that has successfully used Maxent at a regional scale to predict the potential invasion of an insect pest in Colombia. Given the importance of the insect for the region (ICA, 2016), the habitat suitability map can be contrasted with maize cover maps and included in decision-making, such as the distribution of planned corn planting dates and the establishment of a monitoring network for *D. maidis* in the Department. This model can be extended to other regions where the presence of the species has increased to prevent future invasions that would cause disastrous economic losses. The predicted map can also serve as a testable alternative hypothesis for the presence of *D. maidis* in non-infested areas (Kumar *et al.,* 2014).

The findings will be valuable in formulating pest management policies at local, regional, and national levels for maize and other crops in Colombia.

Conclusion

The habitat suitability prediction model for *D. maidis* obtained in this study allowed identifying that among the variables considered, the most important were the topographic diversity index, annual average temperature, reference evapotranspiration, driest month precipitation (July-August-September), annual rainfall, and wind speed. The warmest dry and very dry areas of the Department, which are more favorable for the species were identified, as well as the significance of the driest periods. These most suitable areas coincided with the regions that exhibited the lowest topoclimatic capacity to support species (indicating lower conditions for diversity). Therefore, it is recommended to promote cultural practices for biodiversity to mitigate insect populations by promoting favorable conditions for the establishment of natural enemies and the cultivation of alternative crops or cover crops.

These results help decision-makers and producers to plan the territory and crop management based on knowledge of the risk of *D. maidis* in areas with the characteristics of the variables that predict the habitat suitability of *D. maidis* in the Department. They also help the scientific community to consider this type of studies at a regional level, integrating climatic and biophysical variables with a finer spatial scale.

It is essential to note that this study provides a regional warming for the development of new varieties of *Z. mays* with tolerance or resistance to *D. maidis* and the pathogens that cause maize-stunting transmitted by this insect. For future studies it is important to consider the temporal variation of *D. maidis* in the region to improve prediction models in monthly, weekly or daily scale. Additionally, it is important to link these results to environmental platforms that permit the identification of early warnings for pest management.

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Authors' contribution

Andrea Onelia Rodriguez-Roa: research conceptualization, data collection, study design (leader), data analysis, interpretation of results, review and editing of initial version, review and editing of final version (leader). Approval of final version (all authors). Jhon Mauricio Estupiñan-Casallas: research conceptualization, data collection, study design (leader), data analysis, interpretation of results, review and editing of initial version. Camilo Ignacio Jaramillo-Barrios: research conceptualization, study design, data analysis, data collection, interpretation of results, review and editing of initial version, review and editing of final version. Buenaventura Monje Andrade: data collection, study design, review and editing of initial version, and Carlos Alberto Abaunza González: data collection, data analysis, study design, review and editing of initial version.

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