SUITABILITY AREAS FOR *Candidatus* Liberibacter asiaticus UNDER DIFFERENT CLIMATE CHANGE SCENARIOS IN MEXICO †

[ÁREAS DE IDONEIDAD PARA *Candidatus* Liberibacter asiaticus BAJO DIFERENTES ESCENARIOS DE CAMBIO CLIMÁTICO EN MÉXICO]

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SUMMARY

Background. Climate change models have projected an increase in the distribution of certain crop pests of economic importance by forecasting more favorable future conditions for these organisms. In citrus farming, Huanglongbing is one of the most devastating diseases worldwide, since it has caused the death of millions of trees. **Objetive.** The objective of this study was to estimate the current and future distribution of *Candidatus* Liberibacter asiaticus in Mexico, under the climate change scenarios SSP2 4.5 and SSP5 8.5, for the years 2050 and 2070. **Methodology.** Distribution models were generated with MaxEnt and R, using uncorrelated bioclimatic variables from eight General Circulation Models (GCM) derived from CMIP6 and disease presence data. **Results.** The results indicate that the current suitability is 44.6 %. The future distribution depended on how model predictions were pooled. An optimistic approach that considered the intersection of all models showed a small reduction of 4.1% while, considering the union of all the GCM models, the increase will vary from 12.3 to 20.1 % of the Mexican territory depending on the particular scenario and time projection. **Implications.** The zones of potential occurrence of *Candidatus* Liberibacter asiaticus include most of the citrus-growing areas in Mexico. **Conclusion.** In some regions, future scenarios show a reduction in the potential occurrence of the species in citrus plantations. However, the risk remains because its surroundings include suitable areas that can be sources of dissemination of the disease.
Keywords: bioclimatic variables; citrus; Huanglongbing; potential distribution; species distribution modeling.

RESUMEN

Antecedentes. Los modelos de cambio climático han proyectado incrementos en la distribución de algunas plagas de cultivos de importancia económica, al pronosticar condiciones futuras más favorables para estos organismos. En la citricultura, el Huanglongbing es una de las enfermedades más devastadoras mundialmente, por provocar la muerte de millones de árboles. **Objetivo**. El objetivo del presente trabajo fue estimar la distribución actual y futura de *Candidatus* Liberibacter asiaticus en México, bajo los escenarios de cambio climático SSP2 4.5 y SSP5 8.5 para los años 2050 y 2070. **Metodología**. Se generaron modelos de distribución con MaxEnt y R, utilizando variables bioclimáticas no correlacionadas de ocho Modelos de Circulación General (MCG) derivados del CMIP6 y datos de presencia de la enfermedad. **Resultados**. Los resultados indican que la idoneidad actual fue del 44.6 %. La distribución futura dependió de cómo se agruparon las predicciones de los modelos. Un enfoque optimista, considerando la intersección de todos los modelos mostró una pequeña reducción de 4.1 %, mientras que considerando la unión de todos los MCG, habrá un incremento que variará de 12.3 % a 20.1 % del territorio mexicano dependiendo del escenario y proyección de tiempo. **Implicaciones**. Las zonas de ocurrencia potencial de *Candidatus* Liberibacter asiaticus incluyen la mayoría de las áreas de cultivo de cítricos de México. **Conclusión**. En algunas regiones, los escenarios futuros mostraron una

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reducción del potencial de ocurrencia para las plantaciones de cítricos; sin embargo, el riesgo permanece porque en su entorno existen áreas idóneas que pueden ser focos de diseminación de la enfermedad.
Palabras clave: variables bioclimáticas; cítricos, Huanglongbing; distribución potencial; modelado de distribución de especies.

INTRODUCTION

By increasing the zones that present favorable conditions under certain future climatic scenarios, it is predicted that some crop diseases will increase their coverage (Ghini *et al*., 2011; Contreras-Servín, 2014). As a result, the potential risk of different phytopathogens will rise and there will be a surge in production costs, use of agrochemicals, and environmental contamination as a result (Ghini *et al.*, 2011; Hernández-Mansilla *et al.,* 2017). This has generated a need to research the consequences of climate change on the dynamics of agricultural crop diseases of economic importance (Hernández-Mansilla *et al.,* 2017).

In citrus farming, Citrus Greening or Huanglongbing (HLB) is one of the most devastating diseases worldwide, causing the death of tens of millions of trees and thus the loss of billions of dollars. This disease is generated by the bacteria *Candidatus* Liberibacter africanus, *C.* Liberibacter americanus, and *C.* Liberibacter asiaticus, for which development is differentially affected by temperature (SENASICA, 2019; Ajene *et al.,* 2020; Martínez-Martínez *et al.,* 2021). The former two species are sensitive to high temperatures, while the latter is tolerant to them (Munyaneza *et al.*, 2011; Camacho-Tapia *et al.*, 2016; Granados-Ramírez and Hernández-Hernández, 2018). These differences in sensitivity and tolerance to high temperatures contribute to explaining the geographic distribution of Liberibacter (Camacho-Tapia *et al.*, 2016). Likewise, the distribution of HLB is affected by the presence or absence of its vectors, which are in turn influenced by environmental changes (Ghini *et al*., 2011; Ajene *et al.*, 2020).

The first report of the presence of *C.* Liberibacter asiaticus in Mexico was in 2009 in the state of Yucatán (Contreras-Servín, 2014; Granados-Ramírez and Hernández-Hernández, 2018; SENASICA, 2019). Since then, HLB has been considered a disease that threatens the national citrus industry due to the negative impacts it has on the production of these fruits (López-Collado, 2010). For example, infected young plants fail to produce, and adult plants become unproductive after about two to five years of infection (Iftikhar *et al.,* 2016). The symptoms presented by infected trees include asymmetrical spots, mottled yellowing on the leaves, chlorosis, fruit drop, loss of leaves, and reduction in the size and quality of fruits (Bové, 2006). A study carried out on citrus orchards in Tizimín, Yucatán, found that HLB reduced fruit weight by 17.3 % and juice volume by 18.6 % (Flores-Sánchez *et al.,* 2015). Despite the fact that various investigations related to its control have been conducted, no successful method to cure the disease has been documented. In the course of a few years, the infected trees usually die (Bové, 2006; Contreras-Servín, 2014; Granados-Ramírez and Hernández-Hernández, 2018).

Considering the damage caused by HLB to citrus farming, it is important to conduct studies to assess the potential risk of the disease in Mexico (López-Collado, 2010). One approach to risk analysis is through Species Distribution Modeling (SDM), which enables the identification of potentially suitable areas for the presence of a pest (Pliscoff and Fuentes-Castillo, 2011; Mateo *et al*., 2012; Timaná and Cuentas, 2015). SDM is used to determine how the distribution of the pest may change under future climate scenarios (Ghini *et al.*, 2011). As a consequence, this approach is considered an important tool with which to predict the effects of climate change on the potential distribution of one or several pest species in the geographic space (Villa-Carmona and Cortes-Ortiz, 2014). The results generated by SDM facilitate the surveillance, planning, and management of agricultural areas by determining potentially suitable areas for pest occurrence (Martínez-Martínez *et al.,* 2021). These models are based on statistical and cartographic techniques used to delimit suitable areas (Pliscoff and Fuentes-Castillo, 2011; Mateo *et al*., 2011; Mateo *et al*., 2012) and use data pertaining to species presence and environmental variables as inputs (Villa-Carmona and Cortes-Ortiz, 2014; Becerra-López *et al.*, 2016).

Studies on climatic suitability for HLB using SDM were implemented by Narouei-Khandan *et al.* (2015), who found that large areas of Africa, Latin America, and northern Australia present climates suitable for the development of *Candidatus* Liberibacter asiaticus. In South America, the effect of climate change on the potential distribution of HLB has been evaluated in different periods. It was reported that the risk areas for the establishment of HLB will represent 23 % of the subcontinent by 2050 and 20 % by 2070 (Heit *et al.*, 2016). Research on the distribution of the pathogen *Candidatus* Liberibacter asiaticus in Africa at present and by the year 2050 under the Representative Concentration Pathways 4.5 and 8.5 indicates that extreme changes in climate act to influence the establishment and distribution of HLB, and reveals differences between the current suitability and that of future predictions (Ajene *et al.*, 2020). In Mexico, a potential risk analysis of HLB was carried out using bioclimatic variables, in which it was concluded that the areas with the highest risk are the Pacific coast and the Yucatan peninsula (López-Collado, 2010). Moreover, Martínez-Martínez *et al.* (2021) estimated the potential areas for the establishment of HLB in the state of Tabasco, Mexico; these authors mentioned that the municipalities of Huimanguillo and Balancán are the areas with the greatest potential distribution of the disease and that variables related to temperature have a greater incidence in the distribution. From these studies, we can infer that the current suitability of *C.* Liberibacter asiaticus in Mexico has been examined; however, its future suitability remains to be addressed. The objective of this research was therefore to estimate and contrast the current and future distribution of *C.* Liberibacter asiaticus in Mexico, under two climate change scenarios for the years 2050 and 2070 using eight general circulation models.

MATERIALS AND METHODS

Study area and presence data

The study was carried out in Mexico, with a total land area of 1,964,375 km^2 (INEGI, 2020). Occurrence records were obtained from centroids of 413 municipalities reported with the presence of infested plants and psyllids (SINAVEF, 2017). The use of centroids in SDM is an alternative that can be employed when there are no georeferenced records of presence, but they are reported at the administrative level (Kumar *et al.*, 2014; Quiner and Nakazawa, 2017).

To avoid bias and duplication of information in the results when there is more than one presence record in the same pixel of the predictor layers, a spatial thinning was conducted based on geographic distance, which should be equal to or greater than the layer's resolution (Aiello-Lammens *et al*., 2015). A distance of 5 km was used because the bioclimatic layers have a resolution of 2.5 minutes, approximately equivalent to 4.6 km. The data set was split into 70 % for calibration and 30 % for evaluation of the SDM (Phillips *et al.*, 2006; Jacinto-Padilla *et al*., 2017).

Current predictor variables

Bioclimatic variables were downloaded at a spatial resolution of 2.5 minutes in raster format from the WorldClim page, version 2.1 of the Coupled Climate Models Intercomparison Project (CMIP6) [Table 1]. Subsequently, in the R-4.2.2 software, the 19 layers were clipped to the borders of Mexico and converted to an ASCII format.

To avoid the inclusion of redundant information in the models, it is recommended to only select uncorrelated variables (Wilson, 2011; Peterson *et al*. 2011). Therefore, variables were selected through principal coordinate analysis (PCoA) and the construction of a similarity network based on the Hellinger H index (Wilson, 2011). These analyses used the values of the bioclimatic variables, standardized between 0 and 1, associated with the records of occurrences. The similarity network grouped variables by applying the infomap algorithm (Rosvall *et al.*, 2009). From each group of correlated variables, only one was selected considering its ease of interpretation, a lack of discontinuities in the data (Booth, 2022), and the fact that it was the most important variable for the model calculated with the jackknife method implemented in MaxEnt 3.4.4.

Table 1. Description of the 19 bioclimatic variables.

Code	Description
bio01	Annual mean temperature (°C)
bio02	Mean diurnal range (mean of monthly (max temp - min temp))
bio03	Isothermality (bio02/bio07) (×100)
bio04	Temperature seasonality (standard deviation ×100)
bio05	Max temperature of the warmest month (°C)
bio06	Min temperature of the coldest month (°C)
bio07	Annual temperature range (bio05-bio06)
bio08	Mean temperature of the wettest quarter (°C)
bio09	Mean temperature of the driest quarter (°C)
bio10	Mean temperature of the warmest quarter (°C)
bio11	Mean temperature of the coldest quarter (°C)
bio12	Annual precipitation (mm)
bio13	Precipitation of the wettest month (mm)
bio14	Precipitation of the driest month (mm)
bio15	Precipitation seasonality (coefficient of variation, %)
bio16	Precipitation of the wettest quarter (mm)
bio17	Precipitation of the driest quarter (mm)
bio18	Precipitation of the warmest quarter (mm)
bio19	Precipitation of the coldest quarter (mm)

Selection of climatic models for the future scenarios

Bioclimatic variables for the future scenarios were downloaded from Worldclim version 2.1 of the CMIP6, for the Shared Socioeconomic Pathways (SSP) 2 4.5 and SSP5 8.5, and the years 2050 and 2070. The SSP2 4.5 indicates an intermediate emissions trajectory while the SSP5 8.5 represents the scenario with the highest CO_2 emissions (Riahi *et al.*, 2017). For each scenario, variables were downloaded for eight General Circulation Models (GCM). The models were selected from a total of 23 GCM, based on the construction of clusters of the bioclimatic variables, and using the Hellinger dissimilarity index H (Wilson, 2011). We selected GCM that were distant from each other and that belonged to the same cluster in bio01 (mean annual temperature) and bio12 (annual precipitation), both variables are considered important for modeling organisms (Sanderson *et al*., 2015).

Generation, evaluation, selection, and transfer of the models

The MaxEnt model was used within the kuenm package to generate, evaluate, select, and transfer the best models (Cobos *et al*., 2019). Using the presence data and uncorrelated variables, candidate models were generated exploring all the responses that arose by combining the linear (l), quadratic (q), product (p), threshold (t), and hinge (h). We also tested the regularization multipliers ranging from 0.1 to 10.

For evaluation and selection of the best model, the first filter was to select the statistically significant models that met the partial Receiver Operating Characteristic (ROC) < 5 %. The omission criterion of less than 5 % was then applied to the remaining models. Finally, among the significant and low-omission candidate models, the model with AICc < 2, which is the delta value of the Akaike information criterion corrected for small sample sizes, was selected (Cobos *et al*., 2019). In addition, the model had to have an Area Under the Curve (AUC) value > 0.7, since those with values of AUC from 0.7 to 0.9 are considered good, and higher than 0.9 are very good (Baldwin, 2009). The selected model was transferred to the years 2050 and 2070 under SSP2 4.5 and SSP5 8.5 and bootstrap with 10 replicates applied with a cloglog output format.

Estimation of HLB suitability for current and future scenarios

Present suitability coverage was computed by binarizing the suitability layers through the application of a cut-off threshold of 0.2 (Jacinto-Padilla *et al*., 2017), approximately equivalent to 0.065 of the omission value generated in MaxEnt. For the future scenarios, and to estimate variability in the predictions, the areas of gain, permanence (no change), and loss were subsequently estimated in relation to the current coverage, and two approaches were applied to pool the results. In the first approach, we used the intersection of the models and, in the second approach, we used the union of the models for SSP2 4.5 and SSP5 8.5 for the years 2050 and 2070. The representation of each area was plotted on maps prepared in the ArcGIS 10.5 program. To gain a better comprehension of the behavior of present and future bioclimatic variables for permanence and loss areas, standardized density graphs were also generated and a t-test was applied to each variable associated with random points (n = 3000).

Citrus productive zones and HLB suitability areas

We compared HLB suitability areas with the harvested regions of economically important citrus fruits in Mexico by calculating the citrus-producing regions and then overlapping these with the suitability areas, as described by Rodríguez-Aguilar *et al*. (2023).

RESULTS AND DISCUSSION

Selection of uncorrelated predictor variables

The predictor bioclimatic variables were selected from the six groups found in the similarity network and indicated by the PCoA (Figure 1). These variables were average annual temperature (bio01), diurnal temperature oscillation (bio02), seasonality of temperature (bio04), annual precipitation (bio12), precipitation of the driest period (bio14), and seasonality of precipitation (bio15). The variable bio01 indicates an annual trend and approximates the total energy inputs for a given location; bio02 measures temperature variability, the product of the difference between the maximum and minimum temperature; bio04 refers to the temperature variation over one year according to the standard deviation of the monthly temperature average; bio12 is the sum of the total precipitation of all the months and indicates the quantity of rainwater that falls in a year; bio14 refers to an extreme or limiting environmental factor that identifies the total precipitation that occurs during the driest period, i.e., the period with the lowest total precipitation; and finally, bio15 describes the variation in total monthly rainfall values throughout the year (O’Donnell and Ignizio, 2012).

GCM selected for the future projections

The models that were distant from each other and that belong to the same cluster in bio01 and bio12 were: CNRM-ESM2-1, CanESM5-CanOE, CNRM-CM6-1-HR, MPI-ESM1-2-LR, EC-Earth3-Veg-LR, IPSL-CM6A-LR, CNRM-CM6-1, and MIROC6 (Figure 2). These models were chosen for the future projections since it has been suggested to select a minimum of five models that are distant from each other, and the use of several models allows us to broaden the inference and evaluate the variability in the estimates (Sanderson *et al*., 2015).

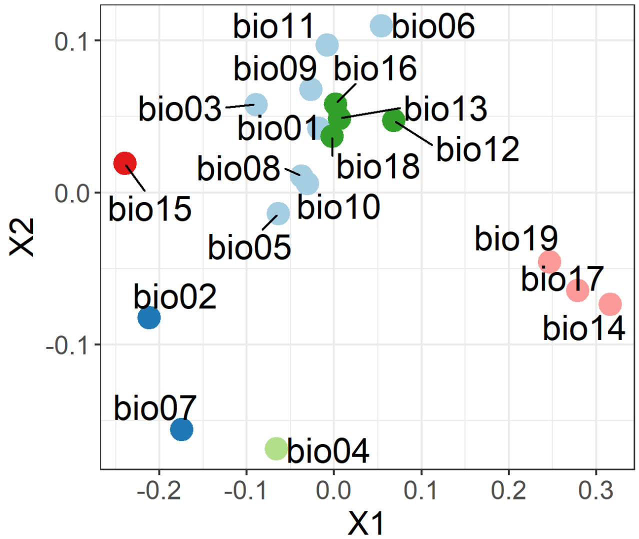

Figure 1. Principal coordinate analysis between the bioclimatic variables. Distance between points indicates the level of relative similarity in the latent variables X1, X2. Bioclimatic variables with the same colors correspond to the same group using the infomap algorithm from network analysis.

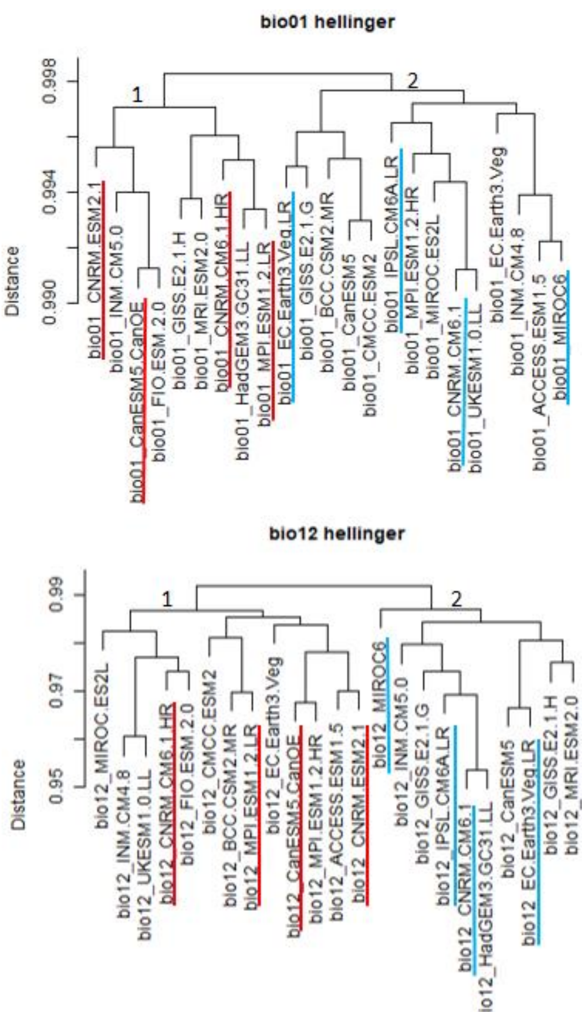

Figure 2. Hierarchical clustering between the General Circulation Models considering the bioclimatic variables bio01 (top) and bio12 (bottom) for the Mexican territory. The underlined models are those that were selected for the study. The red and blue colors refer to the models that match in groups one and two, respectively.

Distribution model and importance of predictor variables

A total of 589 candidate models were created, arising from the combinations among the 19 regularization multipliers and the 31 modeling response types. The best model that met the omission rate and the AICc criterion had a product + threshold (pt) response with a regularization factor of 1. The statistical significance of the model was < 5 %, calculated through the partial ROC; the omission rate was 0.041; the AICc was 8,768.7, and the delta AICc was 0. Finally, the AUC value was 0.88, considered as representing a good model (Baldwin, 2009).

According to the jackknife test, the environmental variable with the greatest gain, when used in isolation, is annual precipitation (bio12). The variable that most decreases the gain of the model when omitted is the average annual temperature (bio01), which indicates that it has the greatest amount of information that is not present in the other variables (Figure 3). These results are similar to those of a study conducted in Africa by Ajene *et al*. (2020), which concluded that the precipitation of the rainiest month (bio13) is the variable with the greatest gain when used in isolation, presenting a strong similarity and correlation with bio12 in this study (1-H= 0.93, r = 0.9). Moreover, according to those authors, bio01 was the variable that most decreased the gain when it was excluded from the model. Moreover, Narouei-Khandan *et al*. (2015) reported that the current climatic suitability of *C.* Liberibacter asiaticus is mainly related to precipitation and temperature. Our results are therefore consistent with those of previous studies since precipitation and temperature are known determining factors in the establishment or development of plant diseases (Ajene *et al.,* 2020).

On the other hand, the MaxEnt response curves indicated how the bioclimatic variables affect the model response (Figure 4). Values of average annual temperature (bio01, Figure 4a) from 24 to 26 °C are those that contribute the most to the model before gradually declining. Within this range is the value of 25.7 °C reported as the optimal condition for plant colonization (Raiol-Junior *et al.,* 2021). The optimal temperature ranges from 20 to 27 °C and has been reported as the most suitable for *Diaphorina citri* populations to spread HLB disease (Hussain *et al*., 2022). Moreover, temperatures below 16 °C did not contribute to the model, since they occur infrequently. This pattern is similar to the vector of the pathogen since low temperatures have been reported to limit the distribution of *Diaphorina citri* (Wang *et al*., 2019, Hussain *et al*., 2022; Rodríguez-Aguilar *et al.,* 2023). According to Nava *et al*. (2007), with the temperature threshold for *D. citri* close to 12 °C. On the other hand, the values from 6 to 14 °C in diurnal temperature oscillation (bio02, Figure 4b) contributed the most to the model. In Mexico, the lowest oscillation values are found in tropical climates, while the maximum oscillation values are located in the northern regions of the country, where dry climates also prevail (García, 2004). Similarly, values of the temperature seasonality below 300 SD (bio04, Figure 4c) contribute more to the model. Regarding annual precipitation (bio12, Figure 4d), it was found that values greater than 500 mm contributed more to the model and stabilized at around 2000 mm. According to Narouei-Khandan *et al*. (2015), the probability of HLB presence increases with higher precipitation, although with some variability. These results indicate that the bacterium has a lower preference for dry climates or areas with low rainfall (Contreras-Servín, 2014; Narouei-Khandan *et al*., 2015; Ajene *et al.,* 2020). Moreover, the precipitation between 20 and 80 mm of bio14 (Figure 4e) had the most influence on the model. These precipitation values in the driest period are more frequent in the group of tropical climates (García, 1998). Finally, precipitation seasonality contribution presented a “U” shape, with higher influence observed at the extreme values (bio15, Figure 4f).

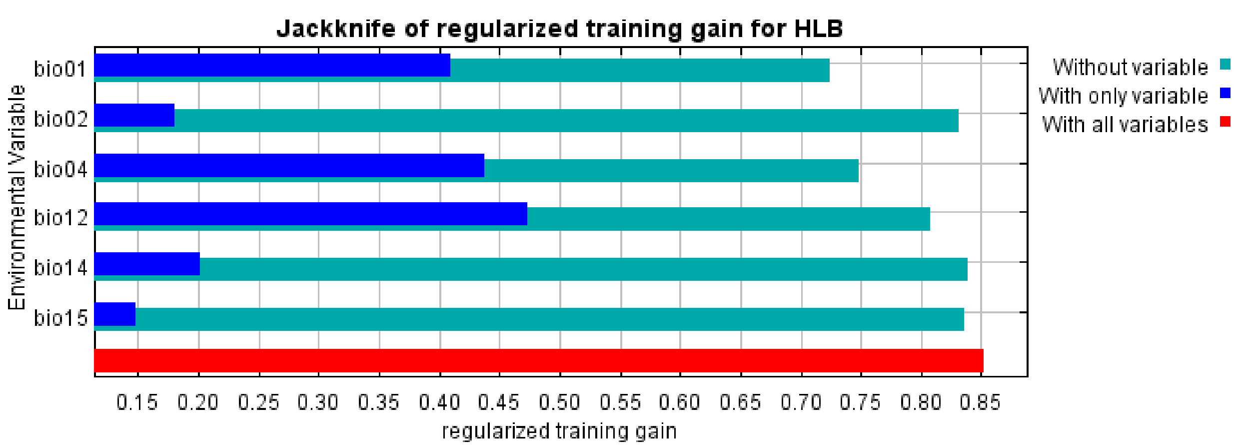

Figure 3. Contribution to the MaxEnt model performance of the six variables used to project the HLB distribution.

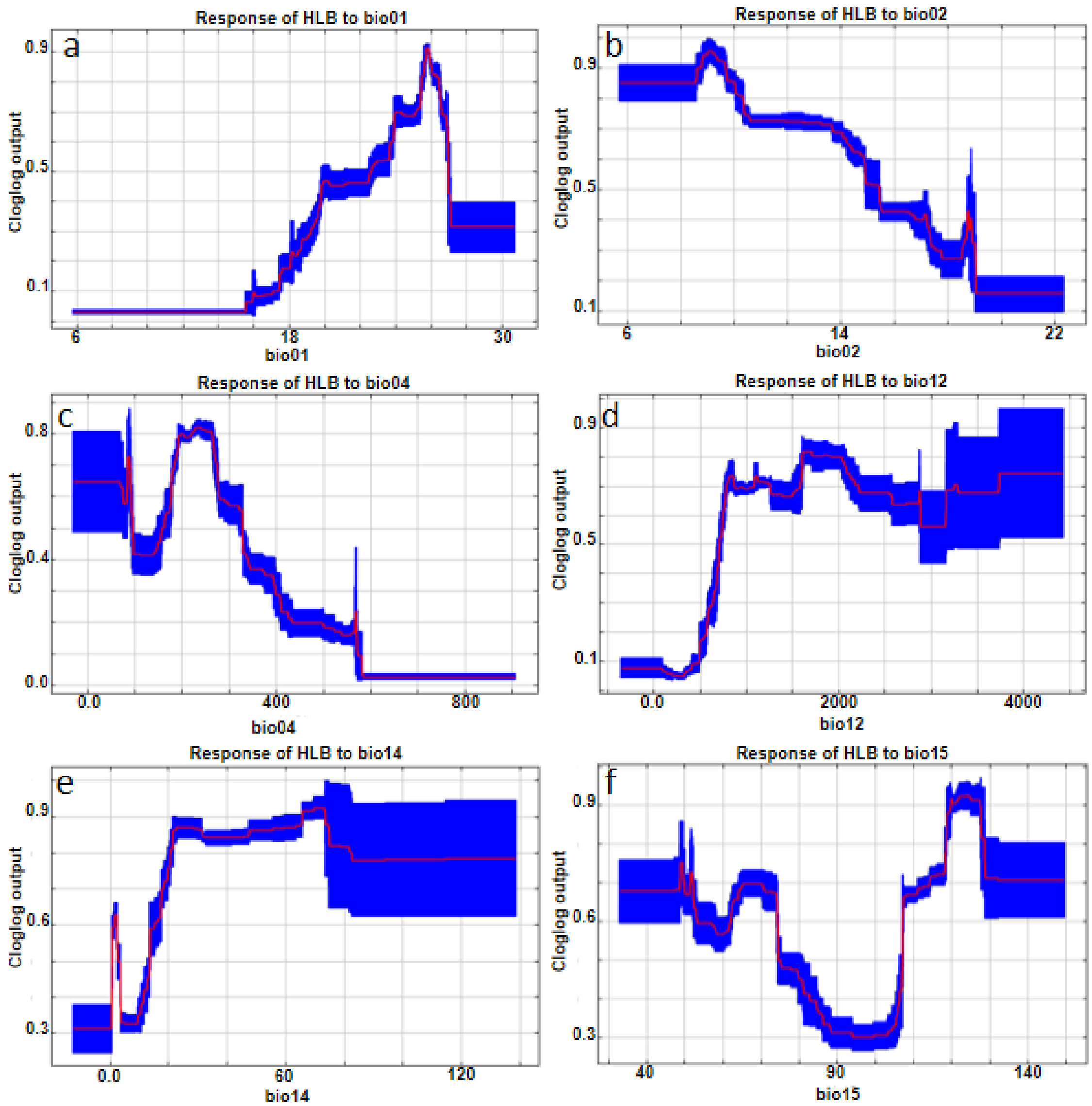

Figure 4. Contribution curves of the variables to the MaxEnt model. (a) average annual temperature (bio01), (b) diurnal temperature oscillation (bio02), (c) seasonality of temperature (bio04), (d) annual precipitation (bio12), (e) precipitation of the driest period (bio14), and (f) seasonality of precipitation (bio15). The red curves show the average response of the 10 MaxEnt runs, while the blue area represents the average ± one standard deviation.

Areas of current suitability of HLB

The estimated area currently suitable for HLB in Mexico is 875,263.02 km^2, equivalent to 44.6 % of the national territory. The potential risk of HLB is found mainly in the Pacific, Gulf of Mexico, and Yucatan Peninsula states (Figure 5a). These regions have also been reported as potentially suitable areas for the establishment of *D. citri*, the vector of the pathogen (López-Collado *et al.*, 2013; Rodríguez-Aguilar *et al.*, 2023). Moreover, the municipalities with the largest number of hectares dedicated to citrus production are distributed there (SIAP, 2020). Therefore, since the environmental conditions suitable for both the vector and the disease coexist in the production areas, the risk of dispersal of the disease among the citrus plantations is high.

The citrus-producing states that have a potential risk of HLB occurrence are Veracruz (VER), Michoacan (MIC), Tamaulipas (TAM), San Luis Potosi (SLP), Nuevo Leon (NLE), Puebla (PUE), Oaxaca (OAX), Colima (COL), Yucatan (YUC), Tabasco (TAB), Guerrero (GRO), Sonora (SON), Jalisco (JAL), Hidalgo (HID), Campeche (CAM), Chiapas (CHP), Quintana Roo (ROO), Sinaloa (SIN), Nayarit (NAY), Baja California Sur (BCS), Durango (DUR), Morelos (MOR), Zacatecas (ZAC), Queretaro (QUE), Estado de Mexico (MEX), Guanajuato (GUA) and Aguascalientes (AGU). These 27 states comprise nearly 554,000 ha of citrus production with a risk of dissemination of the pathogen. Of this area, 327,756 ha are orange; 185,117 ha are lemon; 21,655 ha are mandarin orange, and 19,834 ha are grapefruit (SIAP, 2020). The citrus producing state that does not present climatic suitability is Baja California (BCN), this state was also reported as the entity with the lowest suitability for the *Diaphorina citri* vector (Rodríguez-Aguilar *et al*., 2023).

According to the Köppen classification, as modified by García (1998), 80.4 % of the suitable areas reported in this study coincide or are found in the group of rainy tropical climates (A), while 19.6 % are located in temperate climates (C) and dry (B) (Figure 5a, 5b). According to Contreras-Servín (2014), it has been observed that the tropical climate is the most strongly related to the presence of HLB. The climates of group A are distributed along the coastal regions of the Pacific Ocean (from parallel 29° north toward the south) and the Gulf of Mexico (from parallel 27° toward the south); as well as in the Yucatan Peninsula and Chiapas (García, 2004). The data presented in Figures 5a and 5b show consistency between the results of this study and those published in the literature, since the sampling points located in tropical climates have tested positive for the HLB (Contreras-Servín, 2014).

Future projections

Depending on each region and period, the effect of climate change on diseases can be neutral, positive, or negative (Hernández-Mansilla *et al.*, 2017). This study presents zones with gains, permanence, and losses in relation to the current distribution, depending on how the model matching is considered. For the years 2050 and 2070, under scenarios SSP2 4.5 and SSP5 8.5, the areas of gain predominate in the central and northern part of the country, while the areas with projected losses are located in the Yucatan Peninsula, and near the coasts of the Pacific Ocean and the Gulf of Mexico (Figures 6 and 7).

Analysis of the change in the distributions of the variables between the present and the future with the MIROC6 model for the area of permanence showed that bio01 and bio04 exhibited the greatest differences to the future values (t= 430.76 and t=149.36, p < 0.001). However, these differences did not affect the distribution, since the areas continued to be maintained in the future (Figure 8a). On the other hand, analyzing the loss areas in Figure 7c, it was found that the behavior of these variables was approximately similar to that of the area of permanence (Figure 8b) since bio01 and bio04 continued to present differences (t= 352.03 and t= -34.203, p < 0.001). However, in this loss zone, bio02 presented an increase in value relative to the present (t=179.51, p < 0.001). Consequently, it is inferred that bio02 is probably the variable that determines the loss of suitability areas. As observed in the graphs of Figure 8, bio01 and bio04 presented changes in the area of permanence, but did not affect the distribution. Further studies are therefore required to generate knowledge on how the diurnal temperature oscillation (bio02) affects the distribution and development of HLB, considering that bio02 provides information on the importance of temperature fluctuation for different species (O'Donnell and Ignizio, 2012).

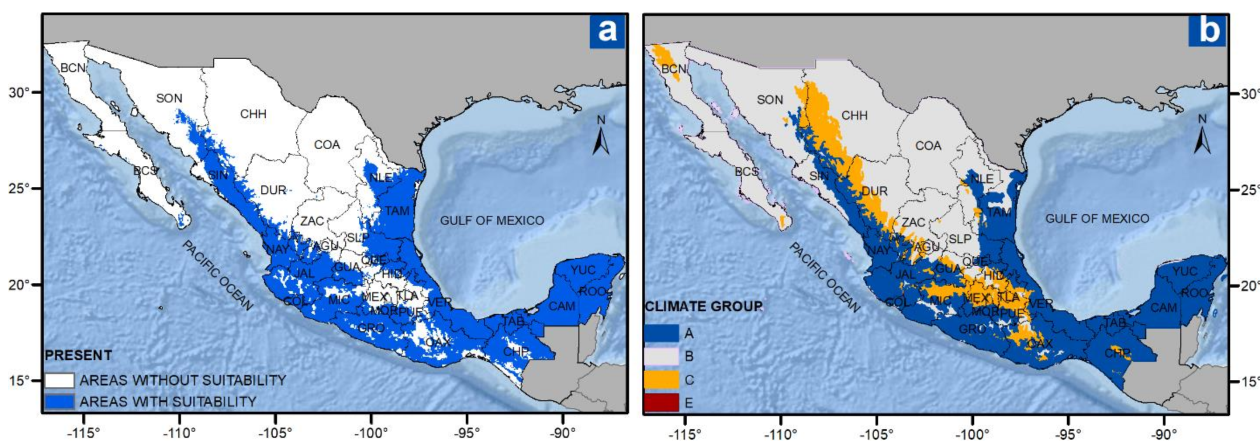

Figure 5. (a) Current potential distribution of HLB in Mexico, in which the suitability areas correspond to MaxEnt values greater than 0.2; (b) Group of climates in Mexico according to the Köppen classification, as modified by García (1998).

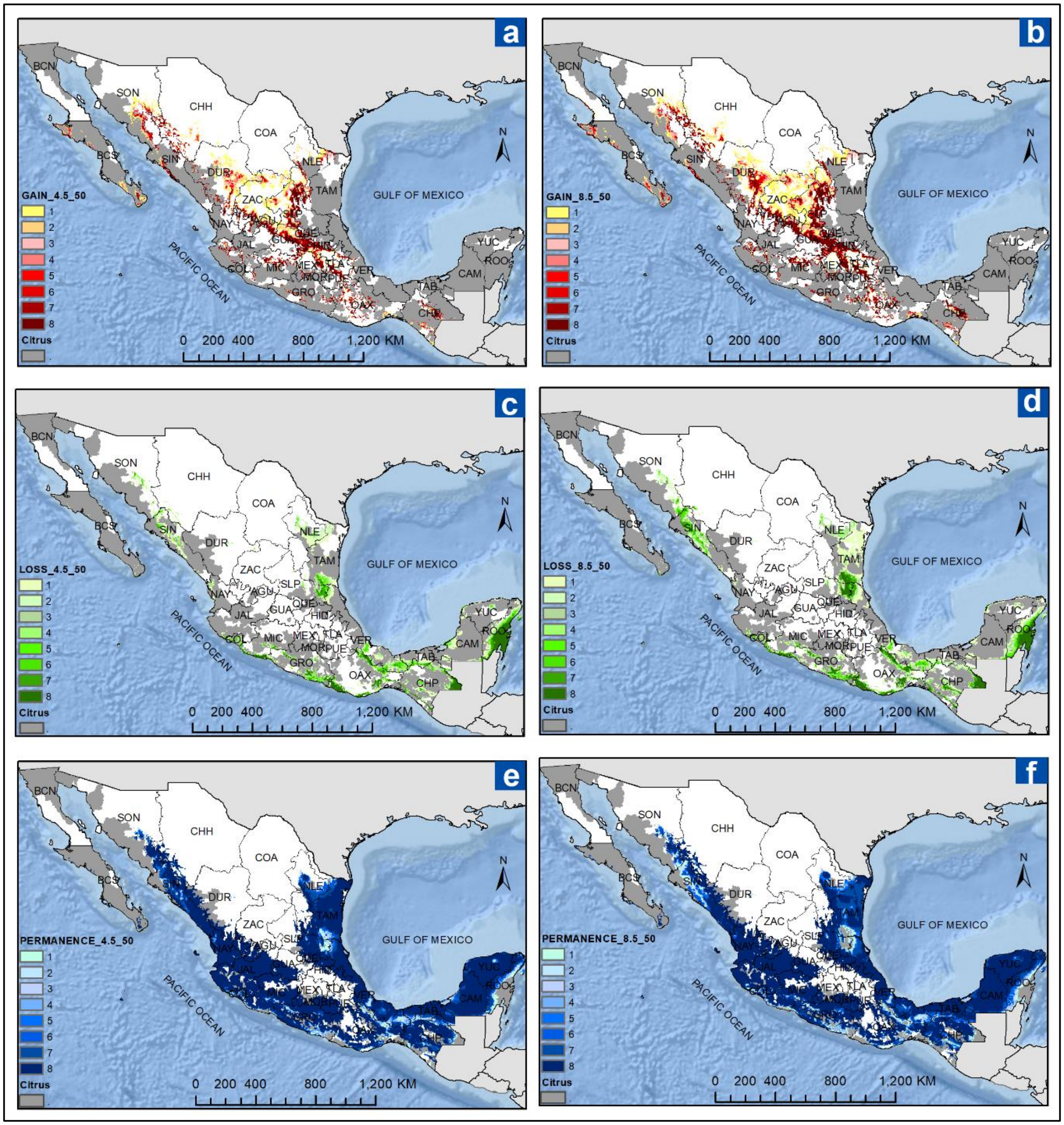

Figure 6. Projection of future HLB suitability areas in Mexico. The color scale refers to the number of models that match permanence, loss, or gain in SSP2 4.5 (a, c, and e) and SSP5 8.5 (b, d, and f) for the year 2050. For example, in map 6a, the number 8 refers to the fact that all eight GCM indicated a gain in those regions. The gray background of the figures represents the municipalities that currently present citrus production (SIAP, 2020).

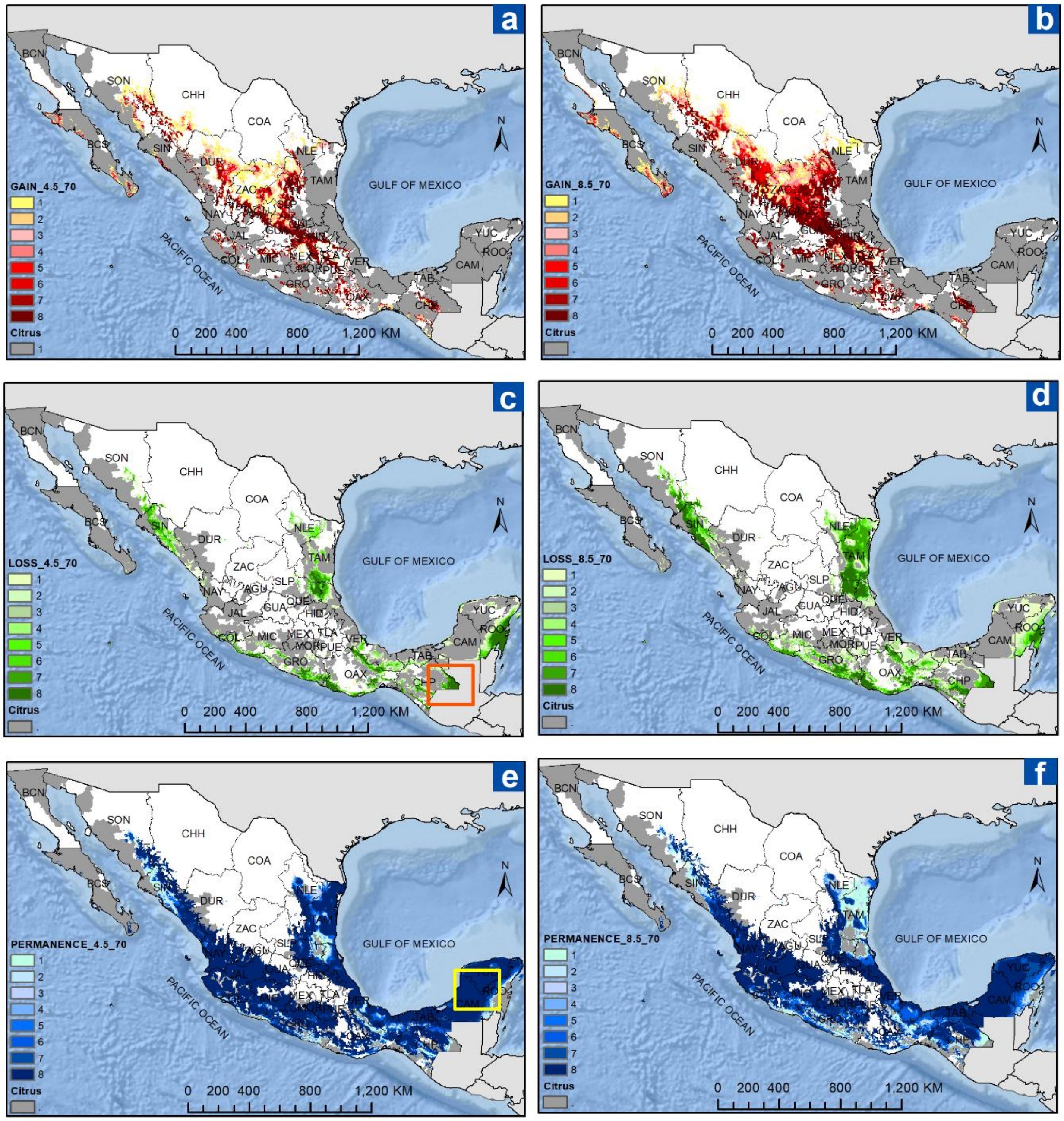

Figure 7. Projection of future HLB suitability areas in Mexico. The color scale refers to the number of models that match permanence, loss, or gain in SSP2 4.5 (a, c, and e) and SSP5 8.5 (b, d, and f) for the year 2070. The gray background of the figures represents the municipalities that currently present citrus production (SIAP, 2020). The orange and yellow boxes in (c, e) delimit regions from which samples were taken to analyze change in the values of the bioclimatic variables for zones of loss and permanence.

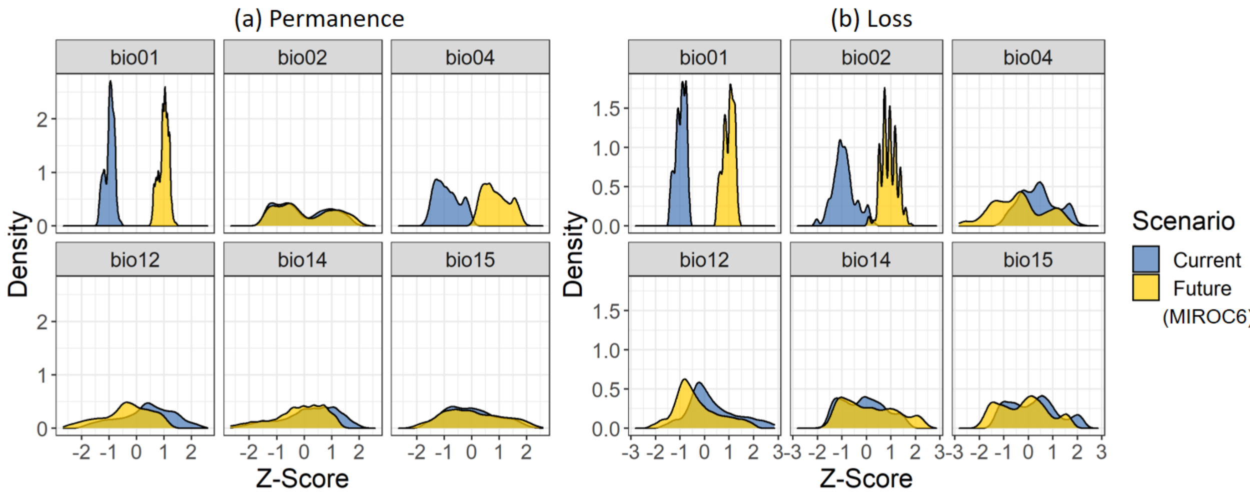

Figure 8. Empirical density distribution of the present and future bioclimatic variables with the MIROC6 model in the areas of permanence (a) and loss (b) derived from random sampling of the areas in the boxes of Figures 7c and e.

On the other hand, in both years (2050 and 2070), it is apparent that the areas of permanence will be greater than those that will be lost relative to the current suitability. It is worth mentioning that the areas of loss are mostly located in tropical climates (Figure 5b) and found within the citrus-producing states (SIAP, 2020). The main citrus-producing states predicted to present a reduction of suitability areas are VER, MIC, TAM, SLP, NLE, OAX, COL, YUC, TAB, GRO, SIN, CHP, ROO, and NAY. These 14 states represent 89.2 % of the harvested area of citrus fruits (SIAP, 2020). However, the risk remains high because these regions will be surrounded by suitability areas that can present sources of dissemination of the disease. In addition, Rodríguez-Aguilar *et al.* (2023) reported that these areas, while not suitable for HLB, will be suitable zones for the establishment of *D. citri*, the vector of the bacteria that causes HLB, and therefore the risk persists.

The areas of gain are found mostly in the municipalities that are not currently producers of citrus (Figures 6 and 7). This result is similar to projections made for *D. citri* in the same scenarios and years; i.e., the areas of gain for the vector are mostly outside the limits of the municipalities dedicated to citriculture (Rodríguez-Aguilar *et al.*, 2023). If the growing areas of citrus do not change in 2050 and 2070, the potential risk of HLB in the new areas will therefore not directly affect agricultural activity. However, if citrus production expands to these zones, the risk of HLB will increase. Moreover, the potential occurrence of the disease in these areas cannot be entirely ruled out because there may be citrus plants in backyard gardens that could act as sources of dissemination to the commercial orchards, considering that control measures to manage the disease and its vector are rarely applied in these backyards (Manjunath *et al.*, 2008; Ajene *et al.*, 2020). According to Hernández-Landa *et al*. (2018), there are rutaceas in some urban areas that host *D. citri*, from where the vector can disperse to citrus plantations.

The future suitability areas are the sum of the permanence and gain areas (blue and red gradients in Figures 6 and 7). Compared with the currently suitable area (875,263.02 km^2) and considering only the areas in which the eight GCM concur, it was found that there will be a reduction of -2.5 % under the SSP2 4.5 scenario, with -3.3 % under SSP5 8.5-50, -2.5 % under SSP2 4.5-70 and -4.1 % under SSP5 8.5-70 in the Mexican territory. When relaxing the coincidence to four GCM models, the trend remained similar; i.e., the future areas will be smaller than the current area since the first scenario presents a reduction of -2 %, the second of -2.8 %, the third of -2 %, and the fourth of -2.9 % (Table 2). Consequently, by considering only the areas where the four and eight GCM agree, the suitable areas under the different projections are reduced.

The previous results were derived from the matching of a certain number of models across the future scenarios. However, in another context of analysis, when the entire agreement gradient between the models is considered; i.e., the total sum of the areas from 1 to 8 represented in Figures 6 and 7, the future projections are greater than the current one. Therefore, the potential increase relative to the current distribution under scenario SSP2 4.5-50 will be 12.3 %, under SSP5 8.5-50 15.7 %, under SSP2 4.5-70 15.6 %, and under SSP5 8.5-70 of 20.1 % of the Mexican territory. In this context, suitability differs in relation to climate change scenarios and years; i.e., for the same year, from SSP2 4.5 to SSP5 8.5, the areas increase and for the same value of SSP from 2050 to 2070, the areas also increase (Table 3). This coincides with that reported

Table 2. Future suitability for HLB derived from the coincidence of eight and four GCM.

GCM number	Scenario	Permanence (km^2)	Loss (km^2)	Gain (km^2)	* Future suitability (km^2)
8	SSP2 4.5-50	754,506.7	138,982.4	71,745.3	826,252.1
8	SSP5 8.5-50	708,587.1	184,902.0	102,036.4	810,623.5
8	SSP2 4.5-70	727,521.7	165,967.4	98,730.3	826,252.1
8	SSP5 8.5-70	636,283.6	257,205.5	158,840.1	795,123.8
4	SSP2 4.5-50	754,506.7	138,982.4	82,329.0	836,835.7
4	SSP5 8.5-50	708,587.1	184,902.0	111,611.0	820,198.2
4	SSP2 4.5-70	727,521.7	165,967.4	108,884.6	836,406.3
4	SSP5 8.5-70	636,283.6	257,205.5	181,295.4	817,579.1

*Future suitability is the sum of permanence and gain.

Table 3. Future suitability for HLB derived from the union of the gradient matching between the GCM.

Scenario	Permanence (km^2)	Loss (km^2)	Gain (km^2)	* Total future suitability (km^2)
SSP2 4.5-50	860,364.4	217,339.8	257,398.7	1,117,763.1
SSP5 8.5-50	850,446.3	271,524.5	333,287.3	1,183,733.6
SSP2 4.5-70	850,338.9	264,268.4	332,106.6	1,182,445.5
SSP5 8.5-70	817,707.9	405,547.9	452,133.0	1,269,840.9

* Total future suitability is the sum of permanence and gain.

by Ajene *et al*. (2020), who concluded that there are more areas suitable for HLB on the African continent under the extreme scenario compared to the moderate scenario of CMIP5. Hence, the increase in suitable area will be greater since an increase is expected in the concentration of atmospheric greenhouse gases.

In the first context, in which the agreement of all models is considered, the approach is the most conservative, since there is a slight reduction in the distribution, and this can be considered the best-case scenario. However, considering any of the GCM matching gradients (a liberal approach), the results show a substantial increase. These two approaches indicate a variability in the predictions which cannot be derived from a single model analysis, as is sometimes reported. It is therefore suggested that climate change studies should include several models since the use of a single model could produce results that do not match with others.

In the future, to achieve improved control of HLB, it is suggested that phytosanitary actions focused on the elimination or reduction of the spread of the disease should consider all areas of agreement among models, and not simply where the eight models match. However, where economic resources allocated to implement phytosanitary actions are limited, it is recommended to pay more attention to the areas in which the eight models agree.

In summary, the prediction of potential areas of suitability for HLB provides information of great utility for the monitoring, planning, and implementation of preventive measures (Narouei-Khandan *et al.*, 2015; Ajene *et al.*, 2020; Martínez-Martínez *et al.*, 2021). In the areas of potential risk of HLB, it is therefore pertinent to carry out the phytosanitary actions recommended by the SENASICA; i.e., epidemiological surveillance in commercial orchards and urban areas, and chemical and biological control of the vector insect in both citrus-producing and urban areas (García-Ávila *et al.*, 2021), since these measures are effective in controlling the spread of HLB (García-Ávila *et al.*, 2021).

CONCLUSIONS

We analyzed the effect of climate on the current and future distribution of HLB. The use of several GCM indicated variability in future projections. The net change ranged from a best-case scenario, in which there is a slight reduction in the future distribution using the intersection of the models, to a high-risk scenario, with a substantial increase in coverage when considering all GCM together. Thus, the variations of future suitability areas vary along a gradient depending on the nature of the GCM matching.

Under the optimistic approach, considering the matching of all the models, we found a marginal reduction in HLB distribution across all scenarios. However, when considering the matching of any of the models, we found the current suitability was 44.6 %, with a substantive increase under all the scenarios. In the first future scenario (SSP2 4.5-50), we found an increase of 12.3 %, in the second scenario (SSP5 8.5-50) 15.7 %, in the third scenario (SSP2 4.5-70) 15.6 %, and in the fourth scenario (SSP5 8.5-70) 20.1 % of the Mexican territory. These regions of potential HLB risk comprise the majority of the citrus-growing zones; however, in some regions, there was a reduction in suitability, and thus the risk for plantations is reduced. Notwithstanding, the risk remains since the suitable and unsuitable areas are geographically close and the risk of dissemination therefore persists.

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