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Research Article
Spatial Distribution of *Diaphorina citri* and Climate Suitability Prediction Using the MaxEnt Model in Indonesia

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Abstract
Background and Objective: *Diaphorina citri*, the Asian citrus psyllid (ACP), is a major vector of Huanglongbing disease in citrus worldwide and controlling this pest in citrus production regions is vital. Effective management requires regular monitoring-mapping its population distribution can support targeted surveillance and control strategies. Conventional population mapping faces challenges, but the maximum entropy model (MaxEnt) offers a valuable predictive tool. This study examined the distribution of ACP in Indonesia and predicted its potential distribution based on local climate suitability using the MaxEnt model. **Materials and Methods:** Field surveys were conducted over two consecutive years, from January, 2022 to December, 2023, in major citrus-producing regions of Indonesia, particularly Bali, Java, Sumatra and Kalimantan. Occurrence data were supplemented with information from published literature. The MaxEnt model was developed using 19 bioclimatic factors and altitude data for Indonesia over 30 years (1970-2000). **Results:** The ACP was found in at least 38 citrus-producing areas across Indonesia. The MaxEnt model demonstrated excellent performance, with a Receiver Operating Characteristic/Area Under the Curve (ROC/AUC) value of 0.917 and identified seven dominant factors related to temperature, rainfall and altitude. Suitability for ACP was predicted to be high in Java, Bali and Nusa Tenggara, while other regions were predicted to have moderate to low suitability. **Conclusion:** Overall, ACP is widely distributed in Indonesia and the MaxEnt modeling effectively reflects its current distribution pattern and enables the prediction of its potential range.

Key words: *Diaphorina citri*, distribution, citrus, climate suitability, MaxEnt

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Diaphorina citri, commonly called Asian citrus psyllid (ACP), is an insect classified under Homoptera[1]. The ACP has a wide host range, encompassing 58 species of plants from the family Rutaceae, which includes various types of citrus and orange jasmine[2]. The ACP is the primary vector of *Candidatus liberibacter* bacteria, which causes huanglongbing (HLB) disease in citrus plants[3,4] . The ACP is currently distributed in at least 40 countries across Asia, Africa, Europe and the Americas[4,5]. This suggests that ACP has become an invasive pest on citrus crops worldwide since its initial discovery in the 18th century in India[4,6]. The HLB, also known in Indonesia as Citrus Vein Phloem Degeneration (CVPD), is a disease that has been present since the 1950s. It is a plant tissue disease caused by infection with the bacterium *Candidatus* Liberibacter. There are at least three species of *Candidatus* Liberibacter that cause HLB: *Candidatus* Liberibacter asiaticus (CLas), *Ca. L. africanus* (CLaf) and *Ca. L. americanus* (CLam)[7]. Citrus HLB has affected citrus production in approximately 40-50 countries worldwide[7-9], including Indonesia. In the Indonesian context, the ACP represents a significant challenge for citrus plantations, with the pest identified as a national control priority. Currently, the cultivation of citrus fruits is practised in various locations across Indonesia, including the islands of Bali, Java, Sumatra, Kalimantan and Sulawesi, with differing production levels in each area[10]. This study provides essential data to support HLB management in Indonesia by applying the maximum entropy model (MaxEnt), a Java-based, open-source machine learning software that models species habitat suitability based on environmental variables[11]. This model has been applied for the prediction of range for invasive species such as cheatgrass (*Bromus tectorum* L.) distribution in Rocky Mountain National Park, Colorado, USA[12], ACP in China[13], conifer *Thuja sutchuenensis* French (Cupressaceae) in China[14], a wetland plant in Korea[15], the bird species White-bellied Sholakili (WBS) *Sholicola albiventris* in India[16] and Ethiopian wolf *Canis simensis* in Ethiopia[17]. This study leverages MaxEnt to generate predictive distribution models of ACP populations tailored to Indonesia's diverse climatic regions. The application of MaxEnt in mapping the distribution of pests, particularly ACP, has not been previously explored. This study thus serves as a pioneering contribution to ACP distribution mapping in Indonesia. The purpose of this study is to map the distribution of ACP populations in Indonesia and to predict regions where the climate is suitable for them based on the MaxEnt model.

MATERIALS AND METHODS

Data collection of ACP presence in Indonesia: Data on *Diaphorina citri* (ACP) presence in Indonesia were collected through direct surveys of citrus plantations conducted from January 2022 to December 2023. The survey[18] covered 206 citrus plantations across four major islands in Indonesia: Java, Bali, Kalimantan and Sumatra. In addition, the ACP occurrence records were determined through a comprehensive review of the published literature from the previous decade to validate and supplement the field data.

Confirmed ACP occurrence data were used as the primary input for the MaxEnt model. Field survey data were georeferenced using Universal Transverse Mercator (UTM) coordinates obtained from Google Earth, including altitude information (height above sea level). Following the rectification of the data, it was stored in CSV format to ensure seamless integration with the MaxEnt software for data retrieval and analysis. The use of the CSV format is a prerequisite for implementing MaxEnt due to its inherent incompatibility with other data formats.

The training data encompasses geolocation information for ACPs worldwide. The data is obtained from the European and Mediterranean Plant Protection Organisation (EPPO) database and subsequently verified using Google Earth. This was particularly important for regions or areas that have undergone a change in nomenclature or coordinate system, such as the United States' transition to the Universal Transverse Mercator (UTM) projection. The verified data were stored in CSV format for subsequent utilisation in MaxEnt.

Environmental data selection: Environmental variables used in this study included 19 bioclimatic variables (Bio1-Bio19), obtained from the World Climate website. The climate data was gathered from climate data for 1970-2000 (WorldClim version 2.1). For datasets not available on WorldClim, particularly for specific periods, the required data were sourced directly from the Climate Research Unit (CRU) at the University of East Anglia. In addition, altitude data were obtained from the Digital Elevation Model (DEM) provided by the United States Geological Survey (USGS) via EarthExplorer (earthexplorer.usgs.gov).

The Bio1-Bio19 variables were clipped to the Indonesian boundary using shapefiles (SHP) from Diva GIS within QGIS software (QGIS Desktop 3.6.2). The clipped bioclimatic layers were then saved in ASCII format for use as environmental inputs in MaxEnt. Similarly, the DEM data were verified and clipped to the Indonesian region using QGIS and exported in ASCII format to serve as an additional environmental layer for the MaxEnt model.

Evaluation and selection of the model: The occurrence database was compiled from the ACP presence data collected in Indonesia. A total of 39 locations were confirmed through field surveillance and literature as input points for MaxEnt, of which 17 were validated as independent occurrence points. This phenomenon can be attributed to the presence of multiple points that were nearby, thus being collectively designated as a single point.

For the "environmental layer" data, bioclimatic data (Bio1-Bio19) and altitude data with a spatial resolution of 2.5 m were utilised. The MaxEnt model was run using the "cloglog" output format and the jackknife procedure to assess variable importance. Duplicate presence records were removed to eliminate adjacent occurrences, ensuring that each validated location represented a unique sample point. Replicates were generated for the 38 input locations, resulting in 17 validated replicates after removing adjacent or overlapping points.

RESULTS

Confirmed ACP locations: The locations of the four main islands where ACP was confirmed are shown in the following table (Table 1). This study identified 39 confirmed points of ACP occurrence based on field surveys and literature records covering the main citrus production areas of the islands of Bali, Java, Kalimantan and Sumatra. The data reveal diverse elevation levels and distinct environmental factors at locations where ACP populations are present. It is noteworthy that specific points are near one another due to the diverse ownership of orange plantations. Consequently, these points are listed independently, even though within the MaxEnt model, they are collectively categorised as one of the closely spaced occurrence points.

The confirmed locations of ACP populations from the 2022-2023 survey also represent the habitat suitability conditions for ACP from the 206 locations visited. The results, which include UTM and altitude data, served as an input in modeling population distribution using MaxEnt. To avoid duplication, the MaxEnt model analysed the 39 validated occurrence points (Table 1), ensuring that only unique and verified data contributed to the model calculations.

Bioclimatic factors influenced the ACP populations in Indonesia: The distribution of *Diaphorina citri* (ACP) populations in Indonesia is influenced by a combination of bioclimatic variables (Bio1-Bio19) and elevation (altitude), as revealed through MaxEnt modeling. Analysis identified seven primary factors, as well as altitude, contributing most to ACP distribution (Fig. 1), including 1). Precipitation-related elements (Bio19/Precipitation of Coldest Quarter; 2). Bio15/Precipitation Seasonality; 3). Bio14/Precipitation of Driest Month); 4). Bio16/Precipitation of Wettest Quarter), 5). temperature (Bio3/Isothermality [BIO2/BIO7] (×100); 6). Bio8/Mean Temperature of Wettest Quarter; and 8). Altitude. These seven factors were obtained from 17 model replications. This was achieved by entering 19 bioclimatic variables and altitude. Altitude was entered as a separate variable. In total, 20 variables were entered. Among the seven dominant factors, Bio19 contributed 46%, Bio15 26.5% and Bio14 11% to the model, indicating that rainfall, temperature and altitude are the main drivers of ACP distribution. These findings align with the occurrence records collected during the study and from existing literature, confirming that both climatic and topographic conditions shape ACP populations in Indonesia.

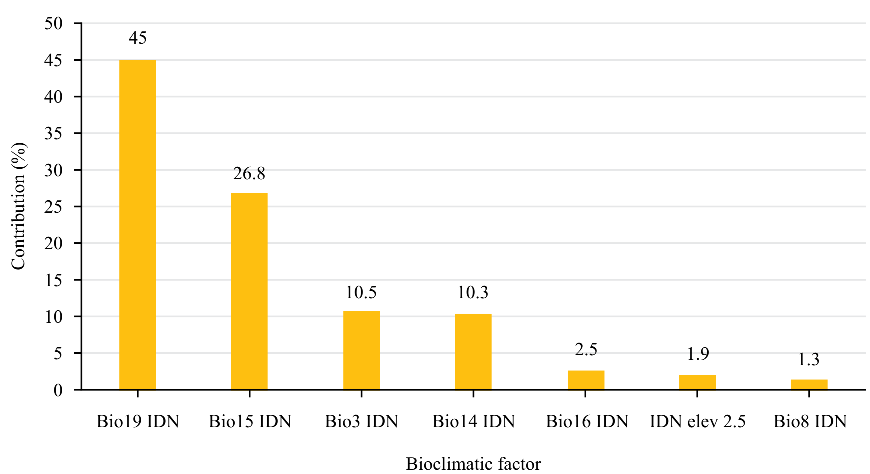

Fig. 1: Seven of the 19 bioclimatic factors tested, as well as altitude, affect the distribution of ACP populations in Indonesia

Table 1: Thirty-nine confirmed ACP population points were used as input in the MaxEnt model fo the distribution of the ACP population in Indonesia

No	Location	Latitude	Longitude	Elevation (m)	Reference
1	West Kalimantan	1.196817	109.14267	3	This study
2	West Kalimantan	1.22355	109.17002	0	This study
3	West Kalimantan	1.223383	109.16997	1	This study
4	West Kalimantan	1.212233	109.17432	2	This study
5	East Java	-8.519483	114.26135	31	This study
6	East Java	-8.463283	114.21892	63	This study
7	Bengkulu	-3.90405	102.32158	3	This study
8	Bengkulu	-3.904267	102.32168	3	This study
9	Bengkulu	-3.904217	102.3219	2	This study
10	Bengkulu	-3.905867	102.31875	2	This study
11	Bengkulu	-3.905750,	102.31995	3	This study
12	Bengkulu	-3.3791	102.4966	900	This study
13	Bengkulu	-3.377317	102.49272	867	This study
14	Bengkulu	-3.902333	102.32632	2	This study
15	Bengkulu	-3.9065	102.33078	2	This study
16	Bengkulu	-3.36135	102.4746	949	This study
17	Central Java	-7.608583	110.20357	264	This study
18	Central Java	-7.608233	110.20318	263	This study
19	Central Java	-7.607783	110.20308	263	This study
20	Central Java	-7.607533	110.20277	263	This study
21	Yogyakarta	-7.7189	110.40163	236	This study
22	Yogyakarta	-7.731183	110.38617	201	This study
23	Yogyakarta	-7.71995	110.40027	231	This study
24	Yogyakarta	-7.719033	110.40165	236	This study
25	Yogyakarta	-7.764383	110.385	146	This study
26	Yogyakarta	-7.769317	110.38112	140	This study
28	Yogyakarta	-7.79635	110.46588	103	This study
29	Yogyakarta	-7.79645	110.46587	103	This study
30	Yogyakarta	-7.796017	110.46593	102	This study
31	Yogyakarta	-7.970022	110.7202	223	This study
32	Yogyakarta	-7.925369	110.39797	98	This study
33	Central Java	-7.772933	110.85287	118	This study
34	East Java	-7.856767	111.48722	111	This study
35	East Java	-7.863133	111.49898	117	This study
36	East Java	-7.86475	111.49717	116	This study
37	Lampung	-6.6987279	107.15363	634	This study
38	Bali	-8.378173	115.28536	658	This study, Wijaya *et al*., 2010[19]
39	Bali	-8.309542	115.30274	1028	This study, Wijaya *et al*., 2010[19]

Validation of the Indonesia *Diaphorina citri* model: The MaxEnt was utilized to calculate the error rate associated with predicting presence and absence. This approach was employed to assess the performance and accuracy of the model. In the ACP population distribution model that was developed, the omission sample is approximately equal to the omission prediction (Fig. 2). This finding indicates that the model exhibits a high degree of proficiency in predicting the suitability of ACP habitats in Indonesia.

The area under the receiver operating characteristic [ROC] curve or the area under the curve (AUC), is a metric that is commonly used to discriminate between presence points and background or absence points across all possible values of a threshold. This provides a threshold-independent assessment of model performance. The AUC value obtained for the model was 0.917, which is well above the value expected for random predictions (Fig. 3). This finding indicates that the model developed is both precise and exceeds the performance of random predictions. This finding underscores the model's capacity to accurately predict the suitability of habitats for ACP in Indonesia. Overall, this model provides a robust framework for identifying areas at risk of ACP establishment and guiding targeted management strategies.

ACP map model and habitat suitability prediction distribution in Indonesia: A significant and readily interpretable outcome of MaxEnt is the habitat suitability map, accompanied by a color index ranging from blue to red, corresponding to habitat suitability. The color scheme employed to denote the suitability of a given habitat is as follows: Blue (0) signifies low suitability, green indicates moderate suitability and red denotes high suitability (1). Within the framework of ACP, this phenomenon can be interpreted as a level of risk, given the fact that ACP is a pest that exerts significant damage to citrus plants.

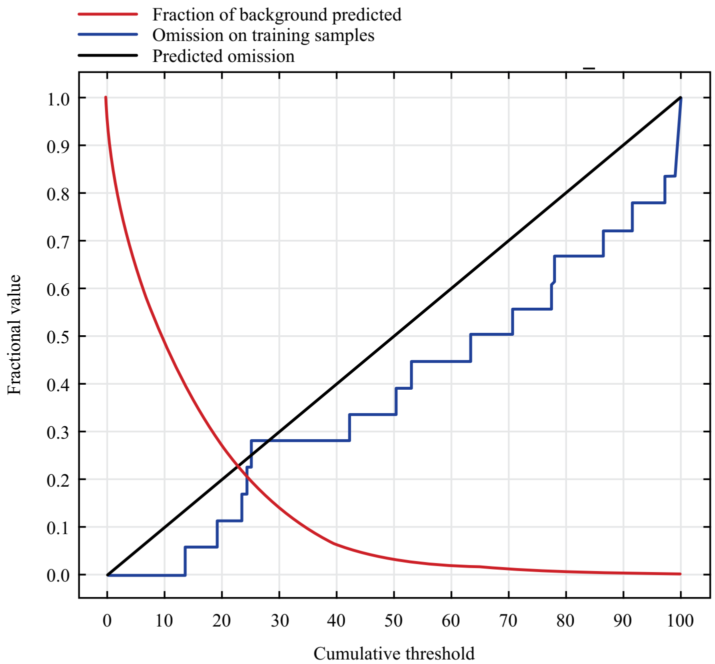

Fig. 2: Omission and predicted area for the model distribution of *Diaphorina citri* in Indonesia

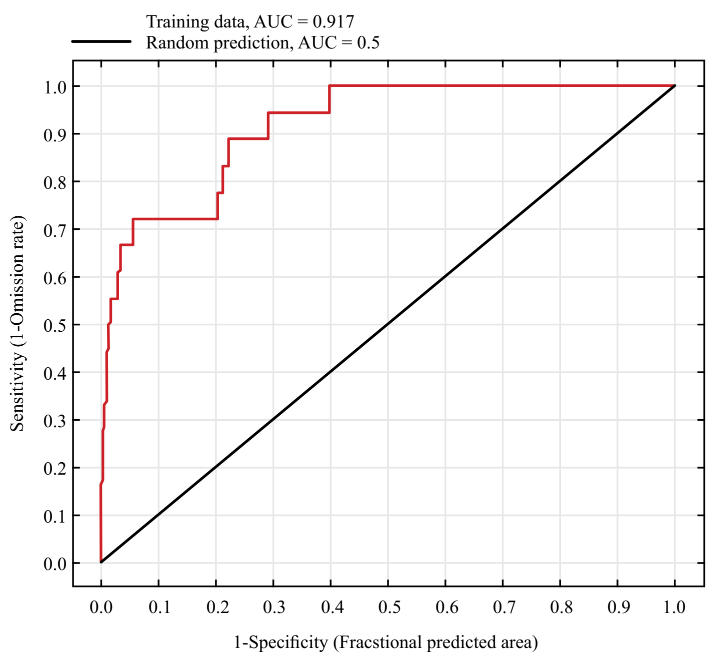

Fig. 3: ROC/AUC value for the ACP distribution model in Indonesia

Table 2: Habitat suitability of ACP populations in Indonesia based on bioclimatic variables and elevation, predicted by the MaxEnt model

Risk category	Provinces
High	West Java, Central Java, Yogyakarta, East Java, Bali, West Nusa Tenggara, East Nusa Tenggara
Moderate	West Sumatra, Bengkulu, South Kalimantan, South Sulawesi, Southeast Sulawesi, Maluku, South Papua
Low	Aceh, North Sumatra, Riau, Riau Islands, Jambi, South Sumatra, Lampung, Bangka Belitung Islands, Banten, Jakarta, West Kalimantan, Central Kalimantan, East Kalimantan, North Kalimantan, West Papua, Papua, Papua Mountains, Central Papua

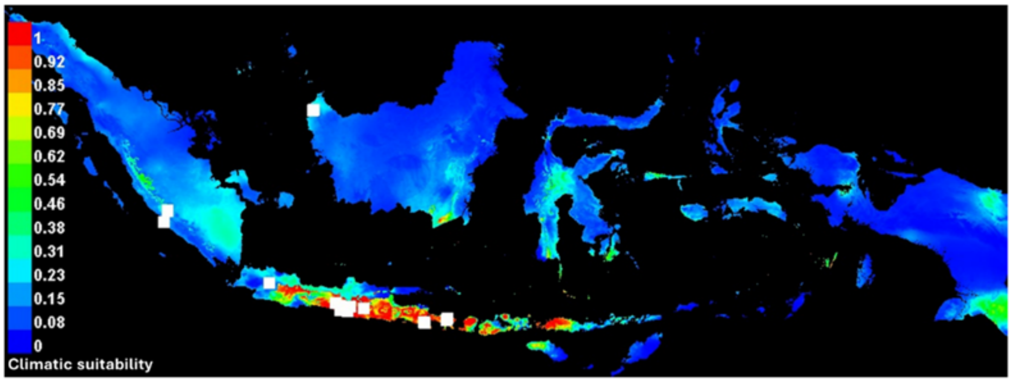

Fig. 4: Habitat suitability map of ACP populations across 38 Indonesian provinces based on bioclimatic and altitude factors

The prediction of ACP habitat suitability in Indonesia indicates that the majority of Java, Bali and Nusa Tenggara are at high risk, while other areas, despite being citrus-producing regions such as Sumatra, Kalimantan, Sulawesi and Papua, are categorized as low to medium risk (Fig. 4). In addition, the ACP habitat suitability data have been categorised according to the Indonesian province system, encompassing a total of thirty-eight provinces (Table 2). This facilitates the detailed framework to assess future risks at the regional level and prioritize surveillance and management efforts for ACP populations.

DISCUSSION

During the period from 2022 to 2023, ACP populations were identified at varying levels in 39 of the 206 surveyed citrus plantations (with these confirmed populations being supplemented by relevant literature) distributed across the primary orange-producing regions of Java, Bali, Bengkulu and West Kalimantan. The number of locations confirmed to have ACP accounts for a mere 5.2% of the total surveyed areas. This finding suggests that ACP populations exhibit significant spatial heterogeneity, particularly between citrus plantations in Indonesia. These populations occur at elevations ranging from 0 (West Kalimantan) to 1,028 m (Bali), spanning both north and south of the equator, with higher abundances generally observed in southern citrus-growing regions. This elevational and climatic diversity highlights ACP's adaptability to a wide range of environmental conditions. The MaxEnt model identified four bioclimatic factors contributing more than 10% to ACP distribution: Bio19 (Precipitation of Coldest Quarter), Bio15 (Precipitation Seasonality), Bio3 (Isothermality) and Bio14 (Precipitation of Driest Month). This phenomenon is widely recognised due to the high precipitation and temperature levels characteristic of tropical regions, including Indonesia. These conditions facilitate the survival and reproduction of ACP. The MaxEnt model for the ACP population in Indonesia exhibits both high quality and consistency with the desired predictions. The model of ACP distribution in Indonesia over the last 30 years shows that climatic factors have an AUC/ROC value of 0.917 (excellent). This indicates that the model's predictions align closely with the actual conditions observed in Indonesia, particularly regarding the distribution of ACP. These findings are consistent with ACP distribution models in other countries, including Australia[19,20], China[4,13] and Mexico[21], reinforcing the robustness of MaxEnt for pest distribution predictions.

The habitat suitability based on the MaxEnt model shows that sites located south of the equator (including Java, Bali and Nusa Tenggara) are very suitable for ACP habitat (high). It can be understood that most ACP locations are found on the island of Java, which is geographically similar to Bali and Nusa Tenggara. These patterns align with prior studies, including Wang *et al.*[4] and Rodríguez-Aguilar *et al.*[20] and global distribution data from the EPPO database, confirming that tropical climates with appropriate rainfall and temperature are primary drivers for ACP habitat suitability.

The habitat suitability based on the MaxEnt model shows that sites located south of the equator (including Java, Bali and Nusa Tenggara) are very suitable for ACP habitat (high). It can be understood that most ACP locations are found on the island of Java, which is geographically similar to Bali and Nusa Tenggara. This means that the more point species are found, the more positively correlated they are to suitability in the resulting MaxEnt model. Currently, at the provincial level, West Java, Central Java, Yogyakarta, East Java, Bali, West Nusa Tenggara and East Nusa Tenggara are predicted to be high-risk areas (high suitability) for ACP populations. Other provinces are categorized as moderate to low risk categories. It is important to monitor these areas, particularly those in the moderate category, to prevent them from becoming high-risk areas in the near future. Integrating occurrence data from field surveys into the MaxEnt model allows for predictive mapping, which can inform proactive ACP management and targeted pest control strategies, providing valuable guidance for the effective management of pests and the prevention of diseases. The ecological niche models provided by MaxEnt are effective for providing an overview of the suitability of a location for ACP populations. This suitability is based on environmental factors (Bio1-Bio19) and confirmed ACP occurrence points. The results of the MaxEnt model in this study are consistent with studies conducted in multiple countries[20-23], demonstrating the model's global applicability However, the current model does not incorporate host availability, agricultural practices or pesticide usage, all of which significantly influence ACP presence and abundance. ACP has a wide host range, including over 40 plant species[24,25] and intensive pesticide use[25-29] can suppress or redistribute populations. Incorporating these variables in future models would enhance predictive accuracy and provide a more comprehensive understanding of ACP ecology.

Overall, this study demonstrates the utility of MaxEnt for mapping ACP distribution and assessing habitat suitability in Indonesia. The results highlight the importance of climatic factors, elevation and host availability in determining ACP populations and provide a foundation for integrated pest management (IPM) strategies aimed at mitigating ACP spread and the associated risk of Huanglongbing disease. Additionally, the study underscores the need for ongoing surveillance, environmental monitoring and incorporation of agronomic practices to refine predictive models and strengthen citrus biosecurity. Subsequent analyses for ACP must consider the heightened significance of climate change. It is essential to integrate climate change projections with predicted shifts in citrus plantings, driven by the anticipated changes in environmental conditions and agricultural adaptation strategies[23]. This holistic approach is predicated on the premise that it will improve early detection, surveillance and climate-smart management of ACP in citrus-growing regions

CONCLUSION

The spatial distribution of ACP in Indonesia covers various citrus-producing areas, including Java, parts of Sumatra, parts of Kalimantan, Bali and Nusa Tenggara. The MaxEnt model, based on bioclimatic factors and elevation, indicates that habitat suitability for ACP populations in Indonesia is potentially very high in Java, Bali and Nusa Tenggara. At the same time, other areas have moderate to low suitability. These findings highlight the heterogeneous nature of ACP distribution across the country. The MaxEnt model provides a robust and comprehensive assessment of potential ACP habitats, offering valuable insights for targeted monitoring, risk assessment and the implementation of integrated pest management strategies in Indonesia's citrus-producing regions.

SIGNIFICANCE STATEMENT

This study provides a comprehensive exploration of the Asian Citrus Psyllid (ACP) population in Indonesia, a topic that has been relatively underreported in the existing literature. By providing detailed, location-specific data, this research enables the precise tracking and monitoring of ACP populations. Furthermore, utilising the Maximum Entropy (MaxEnt) distribution model, this study predicts the potential distribution of ACP across Indonesia, extending beyond citrus-producing areas to encompass a broader geographical scope. This novel approach makes a significant contribution to the field of citrus disease management, particularly in mitigating the impact of ACP and Huanglongbing (HLB), which have been persistent challenges in Indonesia's citrus industry. The findings of this research are expected to inform evidence-based strategies for managing HLB disease and ACP infestations, ultimately supporting the development of more effective and sustainable disease management practices in Indonesia's citrus sector.

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