

Predicting the potential distribution of the Asian citrus psyllid, *Diaphorina citri* (Kuwayama), in China using the MaxEnt model (#34434)

1

First revision

Guidance from your Editor

Please submit by **4 May 2019** for the benefit of the authors (and your \$200 publishing discount).



Structure and Criteria

Please read the 'Structure and Criteria' page for general guidance.



Raw data check

Review the raw data. Download from the location [described by the author](#).



Image check

Check that figures and images have not been inappropriately manipulated.

Privacy reminder: If uploading an annotated PDF, remove identifiable information to remain anonymous.

Files

Download and review all files from the [materials page](#).

- 1 Tracked changes manuscript(s)
- 1 Rebuttal letter(s)
- 4 Figure file(s)
- 2 Table file(s)
- 1 Other file(s)



Structure and Criteria

Structure your review

The review form is divided into 5 sections. Please consider these when composing your review:

1. BASIC REPORTING
2. EXPERIMENTAL DESIGN
3. VALIDITY OF THE FINDINGS
4. General comments
5. Confidential notes to the editor

 You can also annotate this PDF and upload it as part of your review

When ready [submit online](#).

Editorial Criteria

Use these criteria points to structure your review. The full detailed editorial criteria is on your [guidance page](#).





BASIC REPORTING

-  Clear, unambiguous, professional English language used throughout.
-  Intro & background to show context. Literature well referenced & relevant.
-  Structure conforms to [Peerj standards](#), discipline norm, or improved for clarity.
-  Figures are relevant, high quality, well labelled & described.
-  Raw data supplied (see [Peerj policy](#)).

EXPERIMENTAL DESIGN

-  Original primary research within [Scope of the journal](#).
-  Research question well defined, relevant & meaningful. It is stated how the research fills an identified knowledge gap.
-  Rigorous investigation performed to a high technical & ethical standard.
-  Methods described with sufficient detail & information to replicate.

VALIDITY OF THE FINDINGS

-  Impact and novelty not assessed. Negative/inconclusive results accepted. *Meaningful* replication encouraged where rationale & benefit to literature is clearly stated.
-  Data is robust, statistically sound, & controlled.
-  Speculation is welcome, but should be identified as such.
-  Conclusions are well stated, linked to original research question & limited to supporting results.

Standout reviewing tips

3



The best reviewers use these techniques

Tip

Support criticisms with evidence from the text or from other sources

Example

Smith et al (J of Methodology, 2005, V3, pp 123) have shown that the analysis you use in Lines 241-250 is not the most appropriate for this situation. Please explain why you used this method.

Give specific suggestions on how to improve the manuscript

Your introduction needs more detail. I suggest that you improve the description at lines 57- 86 to provide more justification for your study (specifically, you should expand upon the knowledge gap being filled).

Comment on language and grammar issues

The English language should be improved to ensure that an international audience can clearly understand your text. Some examples where the language could be improved include lines 23, 77, 121, 128 – the current phrasing makes comprehension difficult.

Organize by importance of the issues, and number your points

1. Your most important issue
2. The next most important item
3. ...
4. The least important points

Please provide constructive criticism, and avoid personal opinions

I thank you for providing the raw data, however your supplemental files need more descriptive metadata identifiers to be useful to future readers. Although your results are compelling, the data analysis should be improved in the following ways: AA, BB, CC

Comment on strengths (as well as weaknesses) of the manuscript

I commend the authors for their extensive data set, compiled over many years of detailed fieldwork. In addition, the manuscript is clearly written in professional, unambiguous language. If there is a weakness, it is in the statistical analysis (as I have noted above) which should be improved upon before Acceptance.

Predicting the potential distribution of the Asian citrus psyllid, *Diaphorina citri* (Kuwayama), in China using the MaxEnt model

Rulin Wang^{Corresp., Equal first author, 1, 2}, Hua Yang^{Equal first author, 3}, Wei Luo⁴, Mingtian Wang^{5, 6}, Xingli Lu², Tingting Huang¹, Jinpeng Zhao², Qing Li^{Corresp. 1}

¹ Sichuan Agricultural University, College of Agronomy, Chengdu, Sichuan, China

² Sichuan Provincial Rural Economic Information Center, Chengdu, Sichuan, China

³ Sichuan Agricultural University, Key Laboratory of Ecological Forestry Engineering of Sichuan Province/College of Forestry, Chengdu, Sichuan, China

⁴ Zigong Bureau of Meteorology, zigong, Sichuan, China

⁵ Sichuan Meteorological Observatory, Chengdu, Sichuan, China

⁶ Water-Saving Agriculture in Southern Hill Area Key Laboratory of Sichuan Province, Chengdu, Sichuan, China

Corresponding Authors: Rulin Wang, Qing Li

Email address: 398927566@qq.com, 10100@sicau.edu.cn

Background. Citrus Huanglongbing (HLB) is a destructive disease of citrus and a major threat to the citrus industry around the world. This disease accounts for substantial economic losses in China every year. *Diaphorina citri* Kuwayama is one of the major vectors by which citrus HLB is spread under natural conditions in China. Research is needed to identify the geographic distribution of *D. citri* and its major areas of occurrence and to formulate measures for early warning, monitoring and control of this pest and citrus HLB.

Methods. In this study, the ecological niche modelling software MaxEnt (maximum entropy model) was combined with ArcGIS (a geographic information system) to predict the potential geographic distribution of *D. citri* in China. Key environmental factors and the appropriate ranges of their values were also investigated.

Results. Our results show that the training data provided a good forecast ($AUC_{mean} = 0.988$). The highly suitable areas for *D. citri* in China are mainly concentrated to the south of the Yangtze River, and the total area is $139.83 \times 10^4 \text{ km}^2$. The area of the moderately suitable areas is $27.71 \times 10^4 \text{ km}^2$, with a narrower distribution than that of the highly suitable area. The important environmental factors affecting the distribution of *D. citri* were Min Temperature of Coldest Month, Mean Temperature of Coldest Quarter, Precipitation of Wettest Quarter, Mean Temperature of Warmest Quarter, Precipitation of Warmest Quarter, Max Temperature of Warmest Month, and Temperature Seasonality. These results provide a valuable theoretical basis for risk assessments and control of *D. citri*.

Discussion. The predicted results showed that there were highly suitable areas for *D. citri* in Chongqing, Hubei, Anhui and Jiangsu. Therefore, the possibility exists for the further spread of *D. citri* in China in the future. Extreme temperature variables, especially the Min temperature of the coldest month, play an important role in the distribution of *D. citri* and are most closely related to the distribution of *D. citri*.

Predicting the potential distribution of the Asian citrus psyllid, *Diaphorina citri* (Kuwayama), in China using the MaxEnt model

Rulin Wang^{1,2}, Hua Yang³, Wei Luo⁴, Mingtian Wang^{5,6}, Xingli Lu¹, Tingting Huang¹, Jinpeng Zhao², Qing Li¹

¹ College of Agronomy, Sichuan Agricultural University, Chengdu, Sichuan, China

² Sichuan Provincial Rural Economic Information Center, Chengdu, Sichuan, China

³ Key Laboratory of Ecological Forestry Engineering of Sichuan Province/College of Forestry, Sichuan Agricultural University, Chengdu, Sichuan, China

⁴ Zigong Bureau of Meteorology, Zigong, Sichuan, China

⁵ Sichuan Meteorological Observatory, Chengdu, Sichuan, China

⁶ Water-Saving Agriculture in Southern Hill Area Key Laboratory of Sichuan Province, Chengdu, Sichuan, China

Corresponding Author:

Qing Li, Rulin Wang

Wenjiang District, Chengdu, Sichuan, 611130, China

Email address: 10100@sicau.edu.cn; 398927566@qq.com

Abstract

Background. Citrus Huanglongbing (HLB) is a destructive disease of citrus and a major threat to the citrus industry around the world. This disease accounts for substantial economic losses in China every year. *Diaphorina citri* Kuwayama is one of the major vectors by which citrus HLB is spread under natural conditions in China. Research is needed to identify the geographic distribution of *D. citri* and its major areas of occurrence and to formulate measures for early warning, monitoring and control of this pest and citrus HLB.

Methods. In this study, the ecological niche modelling software MaxEnt (maximum entropy model) was combined with ArcGIS (a geographic information system) to predict the potential geographic distribution of *D. citri* in China. Key environmental factors and the appropriate ranges of their values were also investigated.

Results. Our results show that the training data provided a good forecast ($AUC_{mean} = 0.988$). The highly suitable areas for *D. citri* in China are mainly concentrated to the south of the Yangtze River, and the total area is 139.83×10^4 km². The area of the moderately suitable areas is 27.71×10^4 km², with a narrower distribution than that of the highly suitable area. The important environmental factors affecting the distribution of *D. citri* were Min Temperature of Coldest Month, Mean Temperature of Coldest Quarter, Precipitation of Wettest Quarter, Mean Temperature of Warmest Quarter, Precipitation of Warmest Quarter, Max Temperature of Warmest Month, and Temperature Seasonality. These results provide a valuable theoretical basis for risk assessments and control of *D. citri*.

Discussion. The predicted results showed that there were highly suitable areas for *D. citri* in Chongqing, Hubei, Anhui and Jiangsu. Therefore, the possibility exists for the further spread of *D. citri* in China in the future. Extreme temperature variables, especially the Min temperature of the coldest month, play an important role in the distribution of *D. citri* and are most closely related to the distribution of *D. citri*.

Introduction

Diaphorina citri Kuwayama (Hemiptera: Liviidae) is a major pest of Rutaceae plants, including *Citrus reticulata* Blanco, *Citrus sinensis* Osbeck, *Citrus maxima* Merr., and *Murraya paniculata* Jacks (Randa et al., 2017; Yao et al., 2018). *Diaphorina citri* mainly damages the new shoots of citrus plants. Adults occur on the leaves and buds, whereas nymphs cluster on shoots, buds and young leaves. The damaged shoots and buds wither, and the deformed leaves fall off easily, which seriously affects the growth of the plants. The white secretions from the nymphs affect photosynthesis in the branches and leaves (Yao et al., 2018).

In addition to direct feeding damage, the greatest harm caused by *D. citri* is the transmission of the Huanglongbing (HLB) pathogen (Manjunath et al., 2008; Fan et al., 2010). *Diaphorina citri* is one of the major vectors by which citrus HLB is spread under natural conditions in China. The process of transmission of HLB by *D. citri* occurs as follows: after feeding, the HLB pathogen enters the body of *D. citri* through the proboscis and proliferates rapidly in the intestinal epithelial cells; it continues to propagate in the blood chamber and then gradually migrates to other tissues, finally entering the salivary gland. At this time, *D. citri* has the ability to transmit HLB (Luo et al., 2015). The HLB pathogen can circulate, diffuse and proliferate in the body of *D. citri* and has evolved a set of mechanisms to evade the immune system of the pest. When infected *D. citri* feed on healthy plants, the pathogen can be introduced into the plant through the mouthparts of *D. citri* and establish, reproduce and expand in the plant (Song and Luo, 2017).

Citrus HLB is a worldwide citrus disease and is the most harmful and destructive disease in the citrus industry (Luo et al., 2017). As early as the middle of the 18th century, reports were made of citrus HLB in India. At present, citrus HLB occurs in more than 40 countries in Asia, Africa, North America and South America, which seriously threatens the development of the

global citrus industry (Narouei-Khandan *et al.*, 2016). The first report of the occurrence of citrus HLB in China was the 1920s, and the disease has spread rapidly in the southern citrus-producing areas of China. By the end of the 1970s, the disease occurred in Sichuan and Jiangxi except for Guangdong, Guangxi, Fujian, or Taiwan (Hu and Zhou, 2010). At present, 11 of the 19 provinces with citrus cultivation have been harmed by citrus HLB, and the affected area accounts for more than 80% of the total citrus cultivation area (Fan *et al.*, 2009; Cheng *et al.*, 2013). According to reports, citrus HLB occurred in Guangdong Province in 2016, with an area of 8×10^4 hm², resulting in losses of more than 1 billion dollars (Cheng *et al.*, 2016).

Diaphorina citri was first recorded in Taiwan in 1907, and it is also believed to have originated in India (Kuwayama S, 1908; Husain and Nath, 1927). Worldwide, *D. citri* is currently distributed in Asia (China, India, Sri Lanka, Malaysia, Indonesia, Philippines, Bangladesh, Thailand, Iran, Bhutan, Afghanistan, etc.) (Bové, 2006; Sule *et al.*, 2012; Lashkari *et al.*, 2014; Wang *et al.*, 2017; Wang *et al.*, 2018), North America (USA, Mexico, Honduras, Bahamas, Cayman Islands and Jamaica, etc.) (Halbert and Nunez, 2004; López-Collado *et al.*, 2013; Milosavljević *et al.*, 2018), South America (Brazil, Colombia, Ecuador and Paraguay, etc.) (Cornejo and Chica, 2014; Narouei-Khandan *et al.*, 2016), Africa (Kenya, Mauritius and Tanzania, etc.) (Rwomushana *et al.*, 2017; Shimwela *et al.*, 2016) and Australia (Aurambout *et al.*, 2009). In China, *Diaphorina citri* is mainly distributed in Guangdong, Guangxi, Taiwan, Macao, Hong Kong, Fujian, Zhejiang, Jiangxi, Hunan, Guizhou, Yunnan, Sichuan and Hainan (Wang *et al.*, 2016).

Meteorological factors are important environmental factors affecting the distribution, occurrence and development of pests and diseases. Global warming is a long-term increase in the average temperature of the Earth's climate system, an aspect of climate change shown by temperature measurements and multiple effects of warming (Craufurd and Wheeler, 2009). Under the background of climate warming, the suitable areas for pests and diseases are increasing, which leads to the expansion of their geographical distributions (Monteith, 2000). Temperature is one of the main factors restricting the distribution of pests on Earth (Zhang *et al.*, 2012). Climate warming increases the chance of insects restricted by low temperatures to spread to high altitudes (Hu *et al.*, 2015). In recent years, with the increase of winter temperatures, the population of *D. citri* has expanded significantly, and its geographical distribution has spread northward each year, which has aggravated the speed of spread and damage scope of citrus HLB (Chen *et al.*, 2016; Wang *et al.*, 2016). Therefore, research on the influence of climate factors on the distribution of *D. citri* is important.

MaxEnt is a habitat suitability model based on the niche principle. It has high prediction accuracy and can obtain satisfactory results with relatively few distribution points (Elith *et al.*, 2006). The MaxEnt model has been widely used by scholars in China and abroad. Kumar *et al.*, (2014) used MaxEnt to predict the invasion potential of the exotic pest *Phenacoccus solenopsis* Tinsley (Hemiptera: Coccoidea: Pseudococcidae) in India. Penado *et al.*, (2016) used MaxEnt to identify climatically suitable areas for bumblebees in under-sampled parts of the Iberian Peninsula. López-Martínez *et al.*, (2016) studied the environmental suitability for *Agrilus auroguttatus* Schaeffer (Coleoptera: Buprestidae) in Mexico using MaxEnt. Lozier and Mills (2011) used the correlative niche modelling method MaxEnt to predict the geographic distribution of *Epiphyas postvittana* Walker (Lepidoptera: Tortricidae) in its native range and globally and tested model projections using known invasion data. Thus, the MaxEnt model has high accuracy and feasibility in predicting the potential distribution of species.

Recent research on *D. citri* has mainly focused on biological characteristics (Ruan *et al.*, 2012), ecological characteristics (Onagbola *et al.*, 2008), comprehensive control measures (Manjunath *et al.*, 2008; Jia *et al.*, 2015; Wang *et al.*, 2018), the host selection mechanism and the transmission mechanism of HLB (Inoue *et al.*, 2009; Hijaz *et al.*, 2016; Arp *et al.*, 2017; Killiny *et al.*, 2017; Yu and Killiny, 2018); research regarding prediction of its geographical distribution in China is relatively rare. To provide a theoretical basis for such prediction, risk assessments and the effective control of *D. citri*, the MaxEnt model was used to map the potential distribution of *D. citri* in China under current climate conditions, and the relationship between the distribution of *D. citri* and environmental factors was elaborated in this paper.

Materials & Methods

Model selection

MaxEnt is a mathematical model based on maximum entropy theory that uses species distribution data and environmental data to analyse the distribution state of species at maximum entropy (Jayakumar *et al.*, 2015). Petitpierre *et al.* (2012) applied MaxEnt to verify the niche conservation of invasive organisms, and the results showed that MaxEnt was an effective tool for this study and was suitable for analysing the relationship between a species' geographical distribution and climate. Elith *et al.*, (2006) compared the simulation performance of various niche models, and the results showed that MaxEnt had the highest predictive accuracy in 16 models. Zhang *et al.* (2016) used four models, MaxEnt, GARP, BIOCLIM and DOMAIN, to predict the potential habitat of *Pomacea canaliculata* (Gastropoda: Ampullariidae) in China. The results showed that the simulation effect of the MaxEnt model was significantly higher than that of other models. Therefore, MaxEnt was selected as the simulation software for use in predicting the potential distribution of *D. citri* and to analyse the impacts of environmental variables on its distribution.

Environmental variables and species data

In this study, to analyse the climatic suitability regionalization of *D. citri* in China, we chose climatic factors and altitude factors as the initial environmental variables. Data on climate variables and altitude were downloaded from the official WorldClim website (Fick and Hijmans, 2017) (Table S1), which provides the average data from 1950 to 2000.

MaxEnt is a mathematical model based on the principle of climate similarity; it is used to explore the correlation between geographical distribution and environmental variables (Elith *et al.*, 2006). The choice of environmental variables is the key to determining the accuracy of the simulation. Multiple collinearity may exist among the environmental variables, which affects the model's evaluation of response relationships and contribution rates, which in turn affects the accuracy of the simulation (Zhang and Liu, 2017). MaxEnt computes the contribution of predictor variables to model the potential occurrence of a species. In this study, we refer to Zhang and Liu's (2017) method and make some improvements to screen environmental variables. The screening procedure is as follows: 1. Establishment of an initial model to calculate the contribution of the variables to the model (Table 1). 2. Use of ArcGIS to extract the attribute values for 19 variables and SPSS to calculate the Pearson correlation coefficients between any two variables. 3. If a correlation coefficient is greater than 0.8, the most relevant variable is retained according to the percent contribution of the variable in the initial model, and the other variable is excluded. 4. The remaining variables are sorted according to the percent contribution,

and the variables with a percent contribution greater than 1.0 are retained. Through the above procedure and referring to the biological characteristics of *D. citri*, the screening of environmental variables was completed.

To obtain the occurrence records of *D. citri* in China, we accessed two online databases, the European and Mediterranean Plant Protection Organization database (EPPO, <https://www.eppo.int/>) and the Global Biodiversity Information Facility database (GBIF, <https://www.gbif.org/>), and consulted many published articles (Halbert and Manjunanth, 2004; Yang et al., 2006; Wang et al., 2017; Jiang et al., 2018). According to the method described by Jiang et al. (2018) to filter distribution records, we used Google Earth (Collette and Pither, 2015) to proofread the latitude and longitude. In strict accordance with the requirements of MaxEnt, duplicate records, fuzzy records and neighbouring records were removed. Finally, 135 valid records were retained for constructing the models.

Modelling method and statistical analysis

MaxEnt builds a model by means of a machine-learning algorithm to predict the suitability for the occurrence of a given species in a spatial dimension. MaxEnt software (version 3.4.1), which is now open source, was downloaded from the website of the American Museum of Natural History (Phillips et al., 2019); this software has excellent predictive performance for pests and diseases (Jarnevich and Young, 2015).

The specific operational steps for MaxEnt are described herein. First, we imported the occurrence points for *D. citri* and data for 20 variables into the MaxEnt software to create the initial model. In the initial model, the ‘Random test percentage’ was set as 25, and ‘Make pictures of predictions’ and ‘Do jackknife to measure variable importance’ were chosen; the remaining model values were set to default values. Then, we evaluated the percent contributions of the environmental variables to select variables for modelling. Finally, the occurrence points and the selected environmental variables were uploaded to MaxEnt to simulate the distribution of *D. citri* in China. In the final model, “Random seed” was chosen, and 10 replicate models were run. We selected the best model with the highest AUC (Area under the receiver operating characteristic curve) value. The remaining model settings were set to the same as those in the initial model (Kumar and Stohlgren, 2009; Zhu et al., 2018).

ArcGIS software was used to superimpose the index distribution map with China's administrative division map to obtain the suitability regionalization map for *D. citri*. We reclassified the distribution threshold and divided the suitable area into 4 categories, displaying them in different colours according to the method described by Wang et al., (2018).

Analysis of the receiver operating characteristic (ROC) curve is an effective method for evaluating the accuracy of the species distribution model. The method uses the area under the curve (AUC) as the index to measure the model accuracy. The theoretical value range of the AUC is 0.5~1; AUC values closer to 1 indicate a higher prediction accuracy of the model. The evaluation criteria are simulation failure (fail), $0.5 \leq \text{AUC} < 0.6$; poor simulation results (poor), $0.6 \leq \text{AUC} < 0.7$; generally fair simulation results (fair), $0.7 \leq \text{AUC} < 0.8$; good simulation results (good), $0.8 \leq \text{AUC} < 0.9$; and excellent simulation results (excellent), $0.9 \leq \text{AUC} < 1$ (Wang et al., 2007).

Results

Model performance

Figure 1-a shows the ROC curve of the initial model. The AUC values of the training data and the test data are 0.966 and 0.956, respectively. According to the evaluation criteria described in ‘Materials & Methods’, the accuracy of the initial model is “excellent”. Figure 1-b shows the ROC curve of the final model. The results show that the mean AUC value of the 10 replicates was 0.988.

Selection of the environmental variables

Pearson correlation coefficients between the 19 environmental variables are shown in Table 1. The correlation coefficient between temperature seasonality (BIO4) and temperature annual range (BIO7) was greater than 0.8, and BIO7 was excluded according to the screening procedure. The results show that the percent contributions of Mean Temperature of Coldest Quarter, Precipitation of Warmest Quarter, Temperature Seasonality, Precipitation of Driest Month, Precipitation Seasonality, Min Temperature of Coldest Month, Precipitation of Wettest Quarter, and Mean Temperature of Warmest Quarter were higher than 1.0%, and the cumulative sum was 97.2%, which was significantly higher than that of the other variables (Table 2). Previous biological studies have shown that extreme temperature variables play an important role in the distribution of *D. citri* (López-Collado et al., 2013). Therefore, the Max Temperature of Warmest Month was also selected for the final model. Finally, nine variables were selected: Mean Temperature of Coldest Quarter, Precipitation of Warmest Quarter, Temperature Seasonality, Precipitation of Driest Month, Precipitation Seasonality, Min Temperature of Coldest Month, Precipitation of Wettest Quarter, Mean Temperature of Warmest Quarter and Max Temperature of Warmest Month. On this basis, the final model for the distribution of *D. citri* in China was established, and the accuracy of the simulation results was evaluated.

The potential distribution of *D. citri* in China

The selected environmental variables were combined in the MaxEnt model to obtain a suitable index distribution map of *D. citri* in China (Fig. 2). The results showed that the highly suitable areas for *D. citri* in China are mainly concentrated to the south of the Yangtze River, including Guangxi, Guangdong, Hunan, Jiangxi, Fujian, most of Guizhou, north-eastern Hainan, western Taiwan, southern and central Zhejiang, northern Yunnan, east-central Sichuan, most of Chongqing, and Hong Kong (Fig. 2). The total area of the highly suitable area in China is $139.83 \times 10^4 \text{ km}^2$, which occupies 14.52% of the area of the national territory. The moderately suitable areas are mainly distributed in southern Yunnan, southern Hubei, southern Hunan, central Hainan, southern Taiwan, southern Jiangsu and central Zhejiang. The total area of the moderately suitable area is $27.71 \times 10^4 \text{ km}^2$, with a narrower distribution than the most suitable area. The total suitable area (the highly suitable area and the moderately suitable area) is $167.54 \times 10^4 \text{ km}^2$, accounting for 17% of China's total area.

Key environmental variables in the model

The results of the jackknife test can reflect the importance of the environmental variables to the model by calculating the training gains when using ‘with only variable’, ‘without variable’ and ‘with all variables’ for the simulation. Figure 3 is the result of the analysis of the importance of environmental variables to the distribution of *D. citri* according to the jackknife test. It can be seen from the figure that the Min Temperature of Coldest Month is the most important environmental variable affecting the distribution of *D. citri* in China, and its training gain exceeds 1.7. Mean Temperature of Coldest Quarter, Precipitation of Wettest Quarter and Mean

Temperature of Warmest Quarter were also important environmental variables, and their individual training gains were greater than 1.6. The order of importance of the nine environmental variables is Min Temperature of Coldest Month > Mean Temperature of Coldest Quarter > Precipitation of Wettest Quarter > Mean Temperature of Warmest Quarter > Precipitation of Warmest quarter > Max Temperature of Warmest Month > Temperature Seasonality > Precipitation of Driest Month > Precipitation Seasonality.

Environmental variables affecting the occurrence of *D. citri*

The relationship between the probability of *D. citri* occurrence and environmental variables can be evaluated according to the response curve of the environmental factors. Generally, the ecological factor value suitable for the presence of *D. citri* is generally believed to be the value when the probability of the presence of *D. citri* is greater than 0.33.

As shown in Fig. 4, when the Min Temperature of Coldest Month is below -3.58 °C, the probability of *D. citri* presence is less than 0.33. With the increase in Min Temperature of Coldest Month, the probability increased rapidly and reached its highest point at 23.4 °C. The change in the response curve of the Mean Temperature of Coldest Quarter is different from that for the Min Temperature of Coldest Month, and the suitable range of the Mean Temperature of Coldest Quarter is 6.03-17.88 °C. When the temperature is lower than 6.03 °C or higher than 17.88 °C, the probability of *D. citri* occurrence is lower than 0.33 and reaches its highest value at 10.26 °C. When the precipitation of wettest quarter is below 548.66 mm, the probability of *D. citri* presence is lower than 0.33. With an increase in precipitation of wettest quarter, the probability of the presence of *D. citri* increased rapidly and reached its highest value at 619.02 mm. After that, the probability of *D. citri* presence slowly decreases. When precipitation of wettest quarter reaches approximately 1189.75 mm, the probability of the presence of *D. citri* falls below 0.33. Therefore, the suitable range of precipitation of wettest quarter for *D. citri* is 562.89-1189.75 mm.

The trends of presence probability in association with the variables (Mean Temperature of Warmest Quarter, Precipitation of warmest quarter, Max Temperature of Warmest Month, Temperature Seasonality) are similar to that of Mean Temperature of Coldest Quarter, and the suitable ranges were 24.46-34.27 °C, 503.73-1533.58 mm, 28.6-40.91 °C, and 56.83-818.03, respectively (Fig. 4).

Discussion

Evaluation of the MaxEnt model

Commonly used model evaluation indicators include overall accuracy, sensitivity, specificity, kappa, and the TSS (true skill statistic) (Allouche *et al.*, 2006; Wang *et al.*, 2007). The ROC curve is not affected by the threshold and is considered to be one of the best evaluation indicators at present. MaxEnt software can directly draw the ROC curve and calculate the AUC value of the model, which is convenient for judging the predictive effect of the model. Therefore, ROC curves are widely used in the evaluation of MaxEnt models. For example, Wang *et al.* (2017) used ROC curves to evaluate the predictive effect of the MaxEnt model in terms of suitable habitats for the Colorado potato beetle at a global scale; Han *et al.* (2015) used ROC curves to determine the accuracy of niche models in predicting suitable habitats for *Bursaphelenchus xylophilus* Steiner & Bohrer (Tylenchida Thorne: Sphelenchoidae) in China. Therefore, the ROC

curve is used to evaluate the predictive accuracy of the MaxEnt model. The stability of the model is verified by 10 repeated AUC values. The average AUC value of 10 replicated runs of the model was 0.988, which indicates that the simulation effect was “excellent” and proves that the model can be used to simulate the potential distribution of *D. citri* in China.

Predicting the distribution of *D. citri* in China

We used the "extraction" tool in ArcGIS software to identify suitable areas for *D. citri* in China. According to previous study results, the suitable areas were divided into four grades: highly suitable areas, moderately suitable areas, low-suitability areas and unsuitable areas, and the suitable areas of each grade were calculated. The results showed that the highly suitable areas for *D. citri* in China are mainly concentrated to the south of the Yangtze River, and the total area of the highly suitable area in China is $139.83 \times 10^4 \text{ km}^2$. The moderately suitable areas are distributed to the north of the highly suitable areas, and the area is $27.71 \times 10^4 \text{ km}^2$. The total suitable area (the highly suitable area and the moderately suitable area) is $167.54 \times 10^4 \text{ km}^2$ and accounts for 17% of China's total area. Wang *et al.* (2015) applied CLIMEX to predict the potential distribution of *D. citri* in China, and the results were basically consistent with our predictions, with our predicted habitat being more to the north. This difference may have occurred because of the use of different prediction models, species distribution data and environmental variables.

The distribution of *D. citri* in China was investigated by the National Agricultural Technology Extension Service Center in 2014. The results showed that *D. citri* occurred in Zhejiang, Jiangxi, Hunan, Sichuan, Guizhou, Yunnan, Guangxi, Guangdong and Hainan but not in Chongqing and Hubei (Chen *et al.*, 2016). The predicted results showed that there were highly suitable areas for *D. citri* in Chongqing, Hubei, Anhui and Jiangsu. Chongqing and Hubei are located in the core area of the citrus industry belt along the middle and upper reaches of the Yangtze River, which is one of the most suitable areas for citrus cultivation in China (Xiang *et al.*, 2014). By the end of 2017, the cultivated areas of citrus in Hubei and Chongqing were $21.33 \times 10^4 \text{ hm}^2$ and $41.28 \times 10^4 \text{ hm}^2$, respectively (Ding *et al.*, 2017). Therefore, the above two provinces had suitable conditions for the colonization of *D. citri*. Southern Chongqing is adjacent to Sichuan, Chongqing and Hunan, and *D. citri* has been found in these provinces in recent years. Geographically, southern Chongqing is adjacent to Sichuan, Yunnan and Hunan, while southern Hubei is adjacent to Hunan and Jiangxi. *Diaphorina citri* has been found in Sichuan, Yuan, Hunan and Jiangxi in recent years. Since the 1980s, the occurrence boundary of *D. citri* has been moving northward (Chen *et al.*, 2016). Therefore, the possibility of introduction and colonization of *D. citri* in Chongqing and Hubei is very high, and inspection and quarantine work should be strengthened to prevent the introduction of *D. citri* to these regions. Because the climate is not suitable for citrus growth, there is almost no citrus planting in Anhui and Jiangsu, and the suitable areas for *D. citri* in Anhui and Jiangsu are very small (Wu, 2018). Therefore, we speculate that the probability of occurrence of *D. citri* in this area is very low and will not cause serious economic losses.

Hosts of *D. citri* include *Citrus reticulata* Blanco, *Citrus sinensis* Osbeck, *Citrus maxima* Merr., *Murraya paniculata* Jacks, *Murraya exotica* L., and *Clausena lansium* (Lour.) Skeels. These host plants have different effects on the development, reproduction and survival of *D. citri*. Ren *et al.* (2018) investigated the life history of five different host plants. The results showed that the adult longevity of *D. citri* was significantly affected by the host plant and was highest on *C. maxima* and shortest on *C. lansium*, while the survivorship of larvae was highest

(58.10%) on *C. maxima* and lowest on *C. lansium* (46.04%). *Tsai and Liu (2000)* showed that the survival rate of *D. citri* was highest on grapefruit and lowest on lime. *Chen et al. (2011)* measured the feeding preferences of *D. citri* among 13 citrus varieties and found that the number of *D. citri* on the shoots of Newhall navel orange and Fuju was significantly higher than that on the other 11 citrus varieties. These previous studies have shown the importance of host identity for the distribution of *D. citri*, and the analysis of the dependence of *D. citri* on hosts can help to improve the accuracy of predictions. In this paper, we did not simulate the suitable habitats of various hosts of *D. citri* in China, but we can confirm that the main citrus-producing areas cover the suitable habitats of *D. citri* according to the relevant literature. Therefore, the results of this study are still highly reliable.

Environmental variables affecting the geographical distribution of *D. citri*

The occurrence, growth, and spread of plant diseases and insect pests depend not only on the biological characteristics of the disease and pests but also on the host plants, farming systems, management levels and environmental conditions. Meteorological variables are extremely important environmental factors. Under other conditions that are relatively consistent, meteorological factors will become a decisive factor affecting the epidemic or large-scale outbreak of pests and diseases (*Monteith, 2000; Qin et al., 2017*). Studies have shown that abiotic factors such as temperature, humidity and atmospheric pressure can affect the distribution of *D. citri* (*Martini and Stelinski, 2017*), and variables related to temperature are more critical in predictions (*López-Collado et al., 2013*). Therefore, we focus on the effect of temperature on the geographical distribution of citrus as follows.

López-Collado et al. (2013) found that the minimum temperature of the coldest month seemed to be the most important variable affecting the distribution of *D. citri*. In this paper, the importance of environmental variables was tested with the jackknife method. The results showed that the Min Temperature of Coldest Month was the most important variable, indicating that it is most closely related to the distribution of *D. citri*, which is consistent with the result found by *López-Collado et al.* The response curve showed that the probability of the presence of *D. citri* was very low when the Min Temperature of Coldest Month was below -3.58°C, which indicates that extremely low temperatures limit the distribution of *D. citri*. In India, *Atwal et al. (1970)* found that extremely low temperatures were not conducive to the development of the population of *D. citri*. Low temperatures below 0°C played an important role in suppressing the population of *D. citri*, and *Yang et al. (2006)* found the same rule in China. *Bai et al. (2008)* found that the annual minimum average temperature was the main factor limiting the geographical distribution of *D. citri*. *Hall et al. (2011)* noted that the low temperature in winter was the main factor limiting the population growth, geographical distribution and potential transmission of *D. citri*. These results are consistent with the results of this study.

Studies have shown that the damage caused by high temperatures to insects is irreversible and has a certain accumulative effect. Exposure to high temperatures for a long time will lead to a significant decrease in the water content of insects and even their death (*Zhong, 2010; Zhang et al., 2014*). Investigating the effects of high temperature on the mortality and activity behaviour of *D. citri* demonstrated that a high temperature above 40°C leads to a decrease in the survival time of the *D. citri* population (*Kuang et al., 2017*). *Hall et al. (2011)* estimated temperature thresholds for the oviposition of *D. citri* and found that the lower and upper thresholds for oviposition were 16 and 41.6°C, respectively. The results of this study indicate that the Max Temperature of Warmest Month is also a key variable affecting the distribution of *D. citri* and

that the suitable range is 28.6-40.91°C, which is consistent with the above conclusions. *Narouei-Khandan et al. (2016)* showed that the presence of *D. citri* was limited when the mean temperature in the warmest season was higher than 33°C. The response curve of the Mean Temperature of Warmest Quarter showed that the upper limit temperature for the presence of *D. citri* was 34.27°C. This result may have occurred because the larvae and eggs of *D. citri* are more sensitive to high temperatures than adults (*Liu and Tsai, 2000*). In this paper, the response curve shows the effect of a single environmental variable on species distribution, but the growth and distribution of *D. citri* depend on the comprehensive effect of various environmental factors. Therefore, this conclusion cannot fully explain the relationship between *D. citri* and the environmental variables but can be used as a theoretical reference to evaluate the relationship between them.

Conclusions

Based on MaxEnt software and certain environmental data, this study predicts the geographical distribution of *D. citri* in China and aims to provide a scientific reference for the control of *D. citri*.

In this study, the occurrence data of *D. citri* were mainly obtained from EPPO, GBIF, and the literature, and the usable data were much fewer than the available data. The longitude and latitude of some distribution points are obtained by using positioning software, so there is inevitably some geographic error. The basic niche refers to the largest niche that is occupied by a species under the most ideal living conditions. The niche model only analyses the influence of abiotic factors on species distributions, suggesting that the niche predicted by the model is wider than the actual niche occupied by *D. citri*. Therefore, the results of this study have certain limitations and shortcomings.

Studies have shown that in the past 20 years, with increasing global warming, the growth and distribution patterns of the species have changed significantly (*Ma et al., 2013; Zhao et al., 2014; Pacifci, et al., 2017*). The lack of climate data in the past 20 years may lead to a deviation in the conclusions from the actual situation. Therefore, to ensure more reliable prediction results, more comprehensive and accurate distribution data for *D. citri* should be used, and the corresponding missing climate data should be supplemented in the next step.

The autonomous flight ability of *D. citri* is poor, so its dispersal mainly depends on the transportation of plant seedlings and migration with airflow (*Hall and Hentz, 2015*). Therefore, additional work should be performed to prevent the spread of *D. citri*. 1. Quarantine of citrus seedlings should be strengthened to prevent additional dispersal of *D. citri*. 2. All means should be adopted to eradicate *D. citri* in new epidemic areas in a timely and effective manner. 3. In areas adjacent to the epidemic area, it is necessary to monitor *D. citri* to prevent its natural spread. 4. Attention should be paid to monitoring the occurrence of *D. citri* on other hosts in addition to citrus.

Figure Legends

Figure 1:

ROC curve and AUC values for the initial model (a) and the final model (b).

Figure 2:

Occurrence of records of *D. citri* and the potential suitable distribution of *D. citri* in China based on the MaxEnt model. (P) The probability of the suitability in this research.

Figure 3:

Jackknife test for variable importance in the *D. citri* suitability distribution. The values shown are averages over 10 replicate runs.

Figure 4:

Response curves of environmental variables in the MaxEnt models. (A) Min Temperature of Coldest Month (BIO6; °C). (B) Mean Temperature of Coldest Quarter (BIO11; °C). (C) Precipitation of Wettest Quarter (BIO16; mm). (D) Precipitation of Warmest Quarter (BIO18; mm). (E) Max Temperature of Warmest Month (BIO5; °C). (F) Temperature Seasonality (BIO4; °C *100). (G) Mean Temperature of Warmest Quarter (BIO10; °C).

References

- Aurambout JP, Finlay KJ, Luck J, Beattie GAC. 2009. A concept model to estimate the potential distribution of the Asiatic citrus psyllid (*Diaphorina citri* Kuwayama) in Australia under climate change-A means for assessing biosecurity risk. *Ecological Modelling* **220**(19): 2512-2524.
- Arp AP, Martini X, Pelz-Stelinski KS. 2017. Innate immune system capabilities of the Asian citrus psyllid, *Diaphorina citri*. *Journal of invertebrate pathology* **148**: 94-101.
- Allouche O, Tsoar A, Kadmon R. 2006. Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). *Journal of Applied Ecology* **43**(6), 1223-1232.
- Atwal AS, Chaudhary JP, Ramzan M. 1970. Studies on the development and field population of citrus psylla, *Diaphorina citri* kuwayama (Psyllidae: Homoptera). *Journal of Research-Punjab Agricultural University* **7**: 333-338.
- Bové JM. 2006. Huanglongbing: a destructive, newly-emerging, century-old disease of citrus. *Journal of Plant Pathology* **88**(1): 7-37.
- Bai XJ, Deng CL, Lu BG, Zhao XL, Deng GZ, Li GG, Chen CW, Wu RC, Tang Y, Chen GP, Fu HM, Mo JS. 2008. Investigation on the Cold Tolerance of Asian Citrus Psyllid. *South China Fruits* **37**(6): 22-24.
- Cheng CZ, Zeng JW, Zhong Y, Yan HX, Jiang B, Zhong GY. 2013. Research progress on citrus huanglongbing disease. *Acta Horticulturae Sinica* **40**: 1656-1668.
- Cheng BP, Zhao HW, Peng AT, Song XB, Ling JF, Chen X. 2016. Occurrence of Huanglongbing disease and its vector-citrus psylla in citrus orchard of Guangdong Province. *Plant Protection* **42**(1): 189-192.
- Cornejo JF, Chica EJ. 2014. First record of *Diaphorina citri* (Hemiptera: Psyllidae) in ecuador infesting urban citrus and orange jasmine trees. *Journal of Insect Science* **14**(1): 298-298.
- Craufurd PQ, Wheeler TR. 2009. Climate change and the flowering time of annual crops. *Journal of Experimental Botany*, **60**(9), 2529-2539.
- Chen LF, Xu ZX, Wang JG. 2016. Research progress on *Diaphorina citri*. *Guizhou Agricultural Sciences* **44**(6): 42-47
- Collette LKD, Pither J. 2015. Modeling the potential North American distribution of Russian olive, an invader of riparian ecosystems. *Plant Ecology* **216**(10):1371-1383.
- Chen JL, Ruan CQ, Liu B, Fan GC, Duan YP, Hall D. 2011. *Diaphorina citri*'s gost preference on thirteen citrus varieties. *Fujian Journal of Aaricultural Sciences* **26**(2):280-283.

- Ding WY, Yuan B, Zhou YH. 2017. Analysis on growth pattern and trend of fruit industry in China: take citrus for example. *World Agriculture* **12**: 148-155+259-260.
- Elith J, Graham CH, Anderson RP, Dudik M, Ferrier S, Guisan A, Hijmans RJ, Huettmann F, Leathwick JR, Lehmann A, Jin L, Lohmann LG, Loiselle BA, Manion G, Moritz C, Nakamura M, Nakazawa Y, McC. Overton J, Peterson AT, Phillips SJ. 2006. Novel methods improve prediction of species' distributions from occurrence data. *Ecography* **29**(2): 129-151.
- Fan J, Chen C, Brlansky RH, Gmitter FG, Li ZG. 2010. Changes in carbohydrate metabolism in Citrus sinensis infected with 'Candidatus Liberibacter asiaticus'. *Plant Pathology* **59**(6): 1037-1043.
- Fan GC, Liu B, Wu RJ, Li T, Cai ZJ, Ke C. 2009. Thirty years of research on citrus Huanglongbing in China. *Fujian Journal of Agricultural Sciences* **24**(2): 183-190. Hu WZ, Zhou CY. 2010. Advances in the pathogen of citrus Huanglongbing. *Plant Protection* **36**(3): 30-33.
- Fick SE, Hijmans RJ. 2017. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology* **37**(12): 4302-4315.
- Husain MA, Nath LD. 1927. The citrus psylla (*Diaphorina citri*, Kuw.) [Psyllidae: Homoptera] Memoris of the department of agriculture. *Entomological Series* **10**(2): 1-27.
- Halbert SE, Nunez CA. 2004. Distribution of the Asian citrus psyllid, *Diaphorina citri* Kuwayama (Rhynchota: Psyllidae) in the Caribbean Basin. *The Florida Entomologist* **87**(3): 401-402.
- Hu CX, Hou ML, Wei GS, Shi BX, Huang JL. 2015. Potential overwintering boundary and voltinism changes in the brown planthopper, *Nilaparvata lugens*, in China in response to global warming. *Climatic Change* **132**(2): 337-352.
- Hijaz F, Lu ZJ, Killiny N. 2016. Effect of host-plant and infection with 'Candidatus Liberibacter asiaticus' on honeydew chemical composition of the Asian citrus psyllid, *Diaphorina citri*. *Entomologia Experimentalis et Applicata* **158**(1): 34-43
- Halbert SE, Manjunanth KL. 2004. Asian citrus psyllids (Sternorrhyncha: Psyllidae) and greening disease of citrus: A literature review and assessment of risk in Florida. *Florida Entomologist* **87**: 330-353.
- Han YY, Wang Y, Xiang Y, Ye JR. 2015. Prediction of potential distribution of *Bursaphelenchus xylophilus* in China based on Maxent ecological niche model. *Journal of Nanjing Forestry University* **1**: 6-10.
- Hall DG, Wenninger EJ, Hentz MG. 2011. Temperature studies with the Asian citrus psyllid, *Diaphorina citri*: Cold hardiness and temperature thresholds for oviposition. *Journal of Insect Science* **11**(1): 83.
- Inoue H, Ohnishi J, Ito T, Tomimura K, Miyata S, Iwanami T, Ashihara W. 2009. Enhanced proliferation and efficient transmission of *Candidatus Liberibacter asiaticus* by adult *Diaphorina citri* after acquisition feeding in the nymphal stage. *Annals of Applied Biology* **155**(1): 29-36.
- Jia ZC, Zheng JQ, Huang YJ, Zhou HP, Ehsani, R. 2015. Review and prospect of thermotherapy for citrus huanglongbing. *Transactions of the Chinese Society of Agricultural Engineering* **31**(23): 1-9.
- Jayakumar S, Remyaa K, Ramachandran A. 2015. Predicting the current and future suitable habitat distribution of *Myristica dactyloides* Gaertn. using MaxEnt model in the Eastern Ghats, India. *Ecological Engineering* **82**(9): 184-188.
- Jiang HY, Wu FN, Wang YJ, Tao L, Wang JF, Liu Z, Cen YJ., 2018. Research advances on the origin, distribution and dispersal of the Asian citrus psyllid (*Diaphorina citri* Kuwayama). *Journal of Environmental Entomology* **40**(5): 1014-1020.
- Jarnevich CS, Young N. 2015. Using the MAXENT program for species distribution modelling to assess invasion risk. *Pest Risk Modelling and Mapping for Invasive Alien Species* **2015**: 65-81.
- Kuwayama S. 1908. Die psylliden Japans. *Transactions of the Sapporo Natural History Society*, **2**: 149-189.
- Kumar S, Graham J, West AM, Evangelista PH. 2014. Using district-level occurrences in MaxEnt for predicting the invasion potential of an exotic insect pest in India. *Computers and Electronics in Agriculture* **103**: 55-62.

- Killiny N, Hijaz F, El-Shesheny I, Alfaress S, Jones S E, Rogers M E. 2017. Metabolomic analyses of the haemolymph of the Asian citrus psyllid *Diaphorina citri*, the vector of huanglongbing. *Physiological Entomology* **42**(2): 134-145.
- Kumar S, Stohlgren TJ. 2009. Maxent modeling for predicting suitable habitat for threatened and endangered tree *Canacomyrica monticola* in New Caledonia. *Journal of Ecology and Natural Environment* **1**(4), 94-98.
- Kuang F, Lin MQ, Yuan SX, Luo YQ, Zhang N, Lu ZJ, Hu W. 2017. Effects of high temperature on mortality and activity behavior of *Diaphorina citri* kuwayama. *Journal of Southern Agriculture* **48**(9): 1600-1604.
- Luo XZ, Yen AL, Powell KS, Wu FN, Wang YJ, Zeng LX, Yang YZ, Cen YJ. 2015. Feeding Behavior of *Diaphorina citri* (Hemiptera: Liviidae) and Its Acquisition of ‘*Candidatus liberibacter asiaticus*’, on Huanglongbing-Infected Citrus reticulata Leaves of Several Maturity Stages. *Florida Entomologist*, **98**: 186-192.
- Luo L, Gao SJ, Ge YQ, Luo YQ. 2017. Transmission dynamics of a Huanglongbing model with cross protection. *Advances in Difference Equations* **2017**: 355.
- Lashkari, M., Manzari, S., Sahragard, A., Malagnini, V., Boykin, L. M., Hosseini, R. 2014. Global genetic variation in the Asian citrus psyllid, *Diaphorina citri* (Hemiptera: Liviidae) and the endosymbiont Wolbachia: links between Iran and the USA detected. *Pest management science* **70**(7): 1033-1040.
- López-Collado J, López-Arroyo JI, Robles-García PL, Márquez-Santos M. 2013. Geographic distribution of habitat, development, and population growth rates of the Asian citrus psyllid, *Diaphorina citri*, in Mexico. *Journal of insect science* **13**(1):114.
- López-Martínez V, Sánchez-Martínez G, Jiménez-García D, B. Pérez-De la O N. 2016. Environmental suitability for *Agrilus auroguttatus* (Coleoptera: Buprestidae) in Mexico using maxent and database records of four quercus (fagaceae) species. *Agricultural and Forest Entomology* **18**(4): 409-418.
- Lozier JD, Mills NJ. 2011. Predicting the potential invasive range of light brown apple moth (*Epiphyas postvittana*) using biologically informed and correlative species distribution models. *Biological Invasions* **13**(10): 2409-2421.
- Liu YH, Tsai JH. 2000. Effects of temperature on biology and life table parameters of the Asian citrus psyllid, *Diaphorina citri* Kuwayama (Homoptera: Psyllidae). *Annals of Applied Biology* **137**(3): 201–206.
- Miranda MP, Dos Santos FL, Bassanezi RB, Montesino LH, Barbosa JC, Sétamou M. 2017. Monitoring methods for *Diaphorina citri* Kuwayama (Hemiptera: Liviidae) on citrus groves with different insecticide application programmes. *Journal of Applied Entomology* **142**(1-2): 89-96.
- Manjunath KL, Halbert SE, Ramadugu C, Webb S, Lee RF. 2008. Detection of ‘*Candidatus Liberibacter asiaticus*’ in *Diaphorina citri* and its importance in the management of citrus huanglongbing in Florida. *Phytopathology* **98**(4): 387-396.
- Milosavljević I, Amrich R, Strode V, Hoddle MS. 2018. Modeling the phenology of Asian citrus psyllid (Hemiptera: Liviidae) in urban southern California: effects of environment, habitat, and natural enemies. *Environmental entomology* **47**(2): 233-243.
- Monteith JL. 2000. Agricultural meteorology: evolution and application. *Agricultural and Forest Meteorology* **103**(1): 5-9.
- Martini X, Stelinski LL. 2017. Influence of abiotic factors on flight initiation by Asian citrus psyllid (Hemiptera: Liviidae). *Environmental Entomology* **46**(2): 369-375.
- Ma ZF, Liu J, Yang SQ. 2013. Climate Change in Southwest China during 1961–2010: Impacts and Adaptation. *Advances in Climate Change Research* **4**(4):223-229.

- Narouei-Khandan HA, Halbert SE, Worner SP, van Bruggen AHC. 2016. Global climate suitability of citrus huanglongbing and its vector, the Asian citrus psyllid, using two correlative species distribution modeling approaches, with emphasis on the USA. *European Journal of Plant Pathology* **144**(3): 655-670.
- Onagbola EO, Meyer WL, Boina DR, Stelinski LL. 2008. Morphological characterization of the antennal sensilla of the asian citrus psyllid, *Diaphorina citri* kuwayama (Hemiptera: Psyllidae), with reference to their probable functions. *Micron* **39**(8): 1184-1191 .
- Penado A, Rebelo H, Goulson D. 2016. Spatial distribution modelling reveals climatically suitable areas for bumblebees in undersampled parts of the Iberian Peninsula. *Insect Conservation and Diversity* **9**(5): 391-401.
- Petitpierre B, Kueffer C, Broennimann O, Randin C, Daehler C, Guisan A. 2012. Climatic niche shifts are rare among terrestrial plant invaders. *Science* **335**(6074): 1344-1348.
- Phillips SJ, Dudík M, Schapire RE. 2019. [Internet] Maxent software for modeling species niches and distributions (Version 3.4.1). Available from url: http://biodiversityinformatics.amnh.org/open_source/maxent/. Accessed on 2019-2-26.
- Pacifici M, Visconti P, Butchart SHM, Watson JEM, Cassola F, Rondinini C. 2017. Species' traits influenced their response to recent climate change. *Nature Climate Change* **7**(3): 205-208.
- Qin JL, Yang XH, Yang ZW Luo JT, Lei XF. 2017. New technology for using meteorological information in forest insect pest forecast and warning systems. *Pest management science* **73**(12): 2509-2518.
- Rwomushana I, Khamis FM, Grout TG, Mohamed SA, Sétamou M, Borgemeister C, Heya HM, Tanga CM, Nderitu PW, Seguni ZS, Materu CL, Ekesi S. 2017. Detection of *Diaphorina citri* Kuwayama (Hemiptera: Liviidae) in Kenya and potential implication for the spread of Huanglongbing disease in East Africa. *Biological Invasions* **19**(10): 2777-2787.
- Ruan CQ, Chen JL, Liu B, Duan YP, Xia YL. 2012. Morphology and Behavior of Asian Citrus Psyllid,*Diaphorina citri* Kuwayama. *Chinese Agricultural Science Bulletin* **28**(31): 186-190.
- Ren SL, Ou D, Zhang LH, Sang W, Ji QH, Qiu BL. 2018. Effects of different host plants on the development and reproduction of the Asian citrus psyllid *Diaphorina citri*. *Chinese Journal of Applied Entomology* **55**(4): 602-607.
- Song Y, Luo YF. 2017. Advances in the transmission characteristics and mechanism of Candidatus *Liberobacter asiaticus* by *Diaphorina citri* Kuwayama (Hemiptera:Liviidae). *Journal of Environmental Entomology* **39**(4): 955-962.
- Sule H, Muhamad R, Omar D, Hee AKW, Zazali C. 2012. Dispersion Pattern and Sampling of *Diaphorina citri* Kuwayama (Hemiptera: Psyllidae) Populations on Citrus suhuiensis Hort. Ex Tanaka in Padang Ipoh Terengganu, Malaysia. *Pertanika journal of tropical agricultural science*, **35**: 25-35.
- Shimwela MM, Narouei-Khandan HA, Halbert SE, Keremane ML, Minsavage GV, Timilsina S, van Bruggen AH. 2016. First occurrence of *Diaphorina citri* in East Africa, characterization of the *Ca. Liberibacter* species causing huanglongbing (HLB) in Tanzania, and potential further spread of *D. citri* and HLB in Africa and Europe. *European journal of plant pathology* **146**(2): 349-368.
- Tsai JH, Liu YH. 2000. Biology of *Diaphorina citri* (Homoptera: Psyllidae) on four host plants. *Journal of Economic Entomology* **93**(6): 1721-1725.
- Wang YJ, Xu CB, Tian MY, Deng X, Cen Y, He Y. 2017. Genetic diversity of *Diaphorina citri* and its endosymbionts across east and south-east Asia. *Pest management science*, **73**(10): 2090-2099.

- Wang YJ, Lu JM, Beattie GAC, Islam MR, Om N, Dao HT, Van NL, Zaka SM, Guo J, Tian M, Deng X, Tan S, Holford P, He Y, Cen Y. 2018. Phylogeography of *Diaphorina citri* (Hemiptera: Liviidae) and its primary endosymbiont, 'Candidatus Carsonella ruddii': an evolutionary approach to host-endosymbiont interaction. *Pest management science* **74**(9): 2185-2194.
- Wang XL, Li XN, Feng XD, Wu LF. 2016. Investigation on the psyllid, *Diaphorina citri* and Huanglongbing in China. *Plant Quarantine* **30**(2): 44.
- Wang QZ, Liu YM, Li SM, Zhao Y, Wang W. 2018. Chemical composition of essential oil of the invasive plant *Praxelis clematidea* and its repellence and lethality to *Diaphorina citri*. *Chinese Journal of Applied Entomology* **55**(1):117-125.
- Wang YJ, Xu CB, Tian MY, Deng XL, Cen YJ, He YR. 2017. Genetic diversity of *Diaphorina citri* and its endosymbionts across east and south-east Asia. *Pest management science* **73**(10): 2090-2099.
- Wang RL, Li Q, He SS, Liu Y, Wang MT, Jiang G. 2018. Modeling and mapping the current and future distribution of *Pseudomonas syringae* pv. *actinidiae* under climate change in China. *Plos One* **13**(2): e0192153.
- Wang YS, Xie BY, Wan FH, Xiao QM, Dai LY. 2007. Application of ROC curve analysis in evaluating the performance of alien species potential distribution models. *Biodiversity Science* **15**(4): 365-372.
- Wang C, Hawthorne D, Qin YJ, Pan XB, Li ZH, Zhu SF. 2017. Impact of climate and host availability on future distribution of Colorado potato beetle. *Scientific Reports* **7**(1): 4489 .
- Wang SQ, Xiao YL, Zhang HY. 2015. Studies of the past, current and future potential distributions of *Diaphorina citri* Kuwayama (Homoptera: Psyllidae) in China. *Chinese Journal of Applied Entomology* **52**(5): 1140-1148 .
- Wu Y. 2018. Technical efficiency evaluation and influencing factors analysis of citrus p;anting in China. *Chinese Journal of Agricultural Resources and Regional Planning* **39**(9): 99-107.
- Xiang Y, Qi CJ, Lu Q. 2014. The Comparative Advantage and Its Influencing Factors of Citrus Production in Hubei Province. *Economic Geography* **34**(11): 134-139+192.
- Yao TS, Zhou Y, Zhou CY. 2018. Advances in researches on the occurrence and control of asia citrus psyllid. *Journal of Fruit Science* **35**(11): 1413-1421.
- Yu X, Killiny N. 2018. The secreted salivary proteome of Asian citrus psyllid *Diaphorina citri*. *Physiological Entomology* **43**(4): 324-333.
- Yang YP, Huang MD, C Beattie G A, Xia YL, Ouyang GC, Xiong JJ. 2006. Distribution, biology, ecology and control of the psyllid *Diaphorina citri* Kuwayama, a major pest of citrus: a status report for China. *International Journal of Pest Management* **52**(4): 343-352 .
- Zhang L, Huo ZG, Wang L, Jiang YY. 2012. Effects of climate change on the occurrence of crop insect pests in China. *Chinese Journal of Ecology* **31**(6):1499-1507.
- Zhang HT, Luo D, Mu XD, Xu M, Wei H, Luo JR, Zhang JE, Hu YC. 2016. Predicting the potential suitable distribution area of the apple snail *Pomacea canaliculata* in China based on multiple ecological niche models. *Chinese Journal of Applied Ecology* **27**(4): 1277-1284.
- Zhang TJ, Liu G. 2017. Study of methods to improve the temporal transferability of niche model. *Journal of China Agricultural University* **22**(2): 98-105.
- Zhu YJ, W W, Li H, Wang BZ, Yang XH, Liu YS. 2018. Modelling the potential distribution and shifts of three varieties of *Stipa tianschanica* in the eastern Eurasian Steppe under multiple climate change scenarios. *Global Ecology and Conservation* **16**: e00501.
- Zhong JH. 2010. Heat tolerance of *Coccobius azumai* Tachikawa adult. *Journal of Fujian Agriculture and Forestry University (Natural Science Edition)* **39**(5): 465-470.
- Zhang HN, Lv JH, Ya CC, Ma D, Bai XG. 2014. Effect of high-temperature treatment on mortality and moisture content of *Sitophilus Zeamais*. *Journal of Henan University of Technology (Natural Science Edition)* **35**(6): 45-48.

665 Zhao HY, Guo JQ, Zhang CJ, Sun LD, Zhang XD, Lin JJ, WangYH, Fang F, Ma PL, Liu CH, Li YC,
 666 Fang JG, Li L, Li HM, Zheng GF, Deng ZY, Dong AX. 2014. Climate Change Impacts and
 667 Adaptation Strategies in Northwest China. *Advances in Climate Change Research* 5(1):7-16.

Figure 1

ROC curve and AUC values for the initial model (a) and the final model (b)

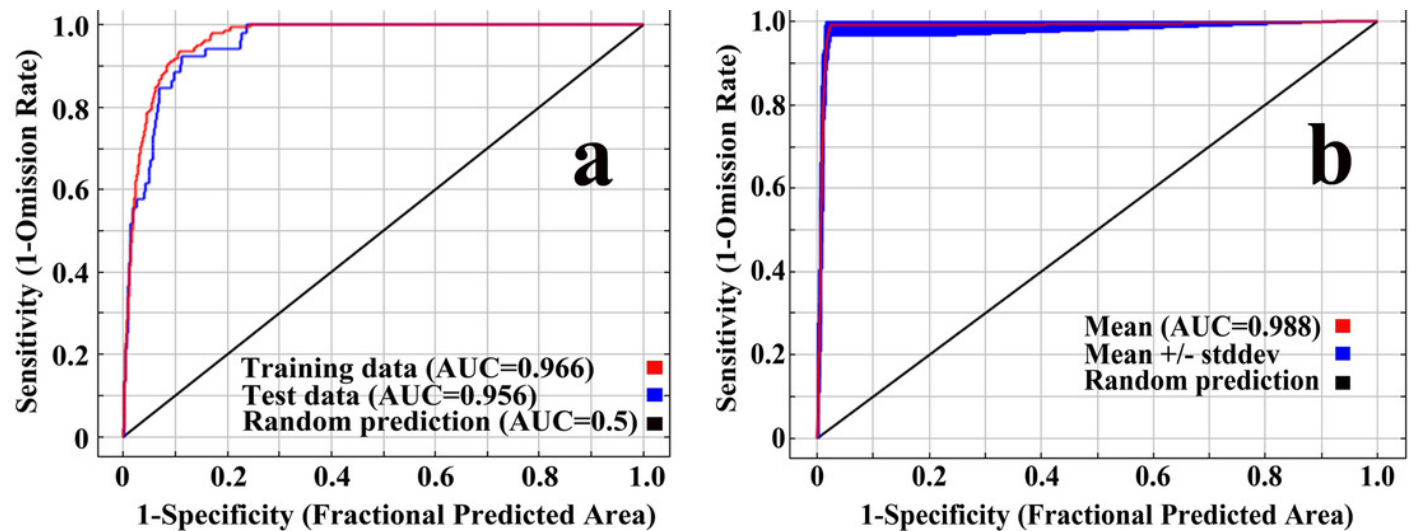


Figure 2

Occurrence of records of *D. citri* and the potential suitable distribution of *D. citri* in China based on the MaxEnt model.

(P) The the probability of the suitability in this research.

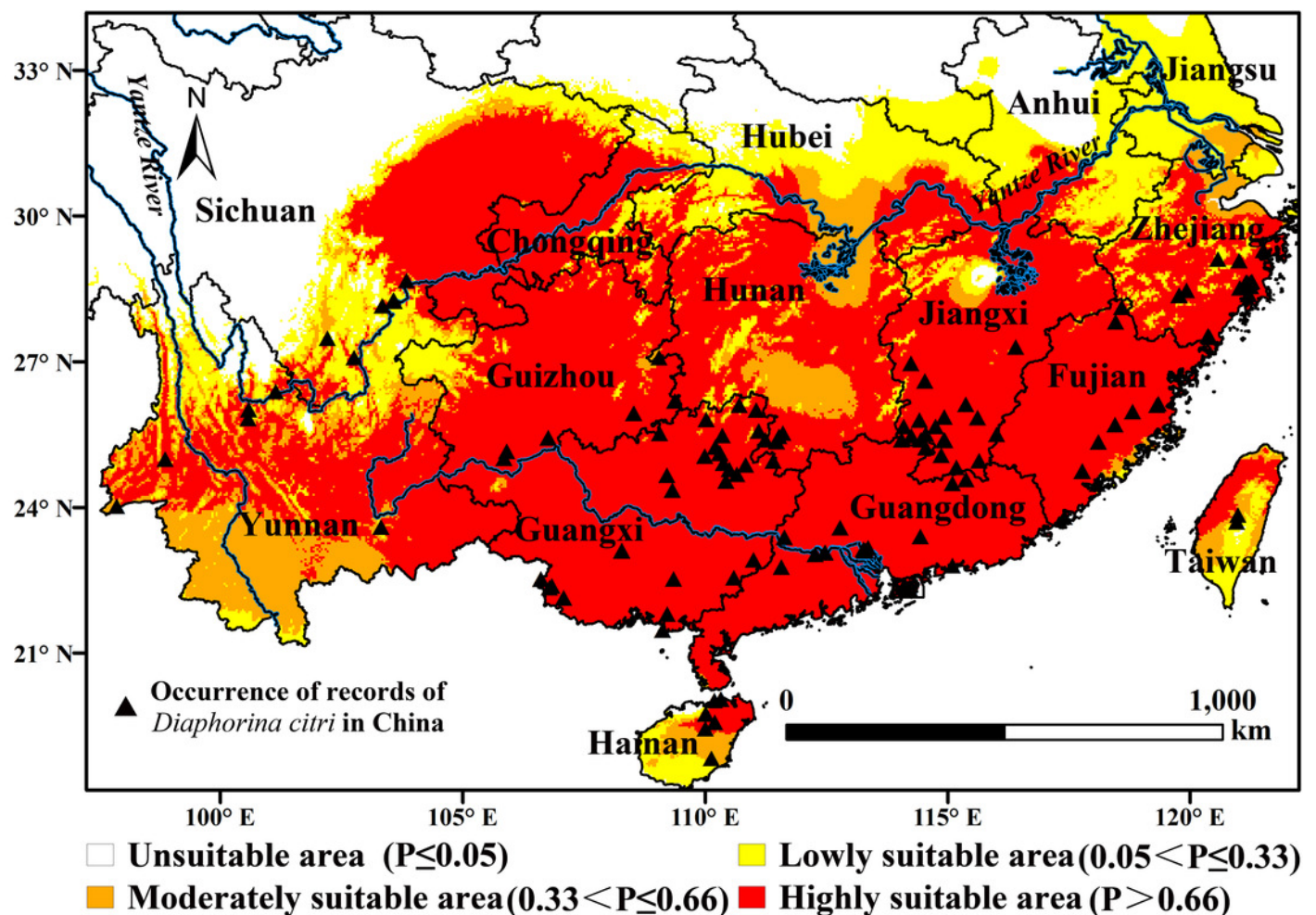


Figure 3

Jackknife test for variable importance in the *D. citri* suitability distribution.

The values shown are averages over 10 replicate runs.

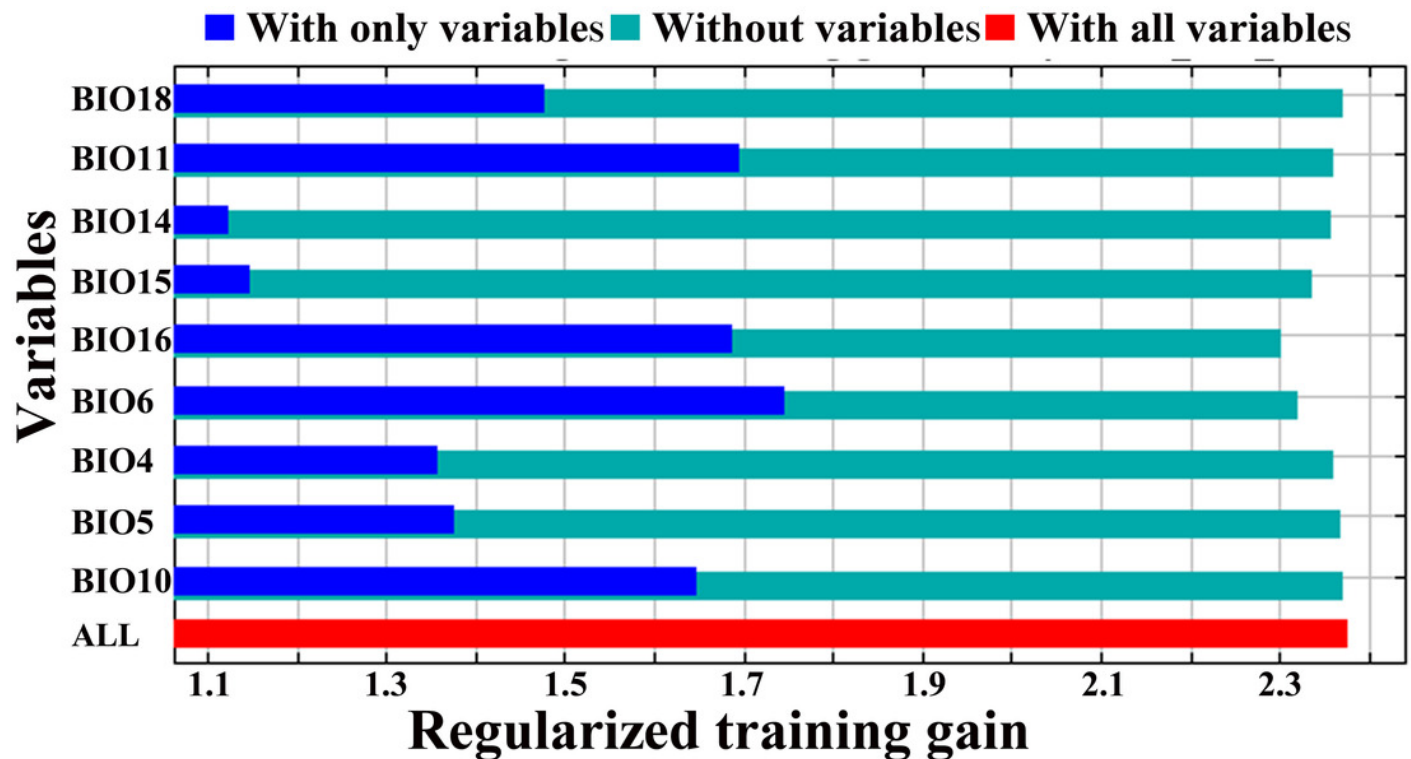


Figure 4

Response curves of environmental variables in the MaxEnt models.

(A) Min Temperature of Coldest Month (BIO6; °C). (B) Mean Temperature of Coldest Quarter (BIO11; °C). (C) Precipitation of Wettest Quarter (BIO16; mm). (D) Precipitation of Warmest Quarter (BIO18; mm). (E) Max Temperature of Warmest Month (BIO5; °C). (F) Temperature Seasonality (BIO4; °C *100). (G) Mean Temperature of Warmest Quarter (BIO10; °C).

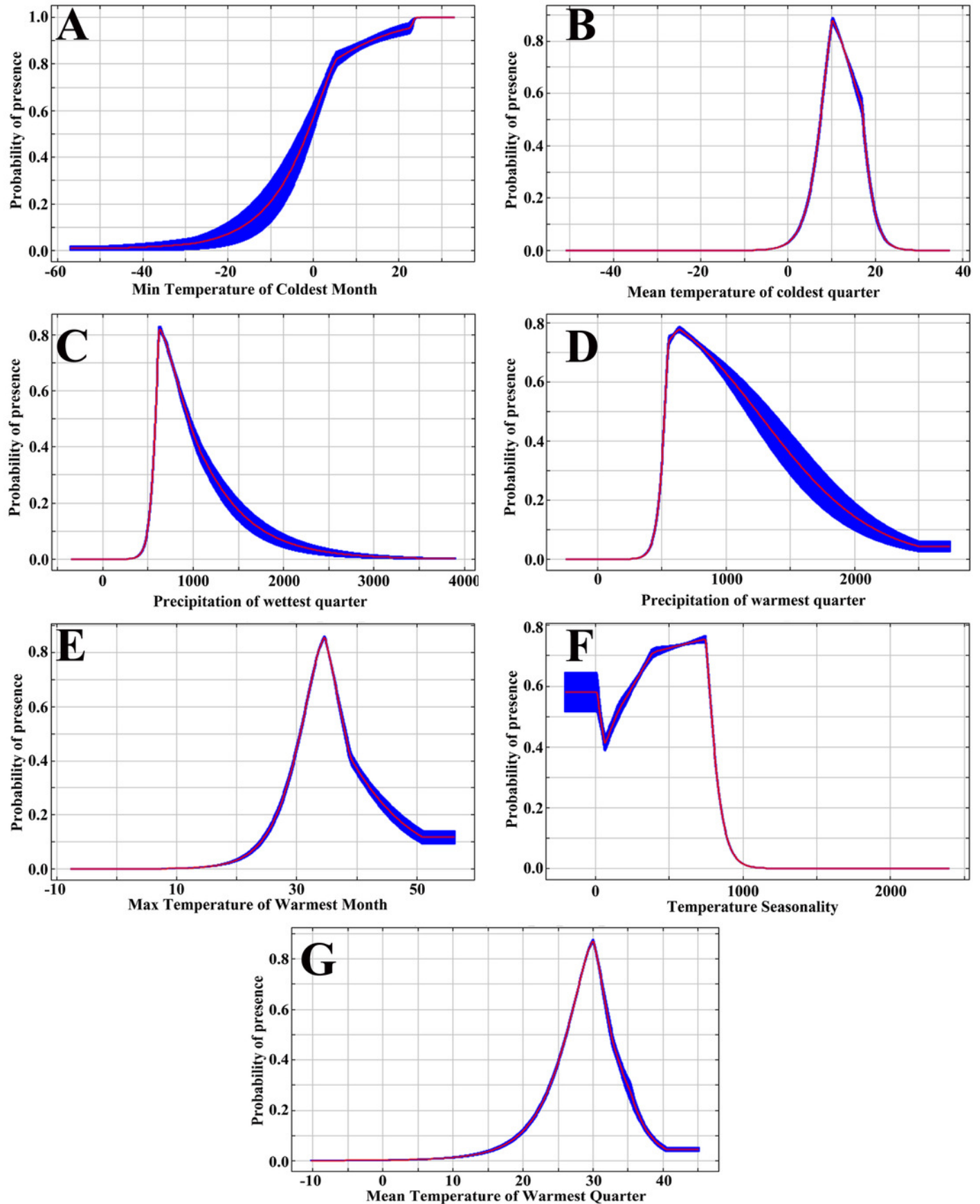


Table 1 (on next page)

Pairwise Pearson's correlation coefficients of environmental variables.

BIO1: Annual Mean Temperature; BIO2: Mean Diurnal Range; BIO3: Isothermality; BIO4: Temperature Seasonality; BIO5: Max Temperature of Warmest Month; BIO6: Min Temperature of Coldest Month; BIO7: Temperature Annual Range; BIO8: Mean Temperature of Wettest Quarter; BIO9: Mean Temperature of Driest Quarter; BIO10: Mean Temperature of Warmest Quarter; BIO11: Mean Temperature of Coldest Quarter; BIO12: Annual Precipitation; BIO13: Precipitation of Wettest Month; BIO14: Precipitation of Driest Month; BIO15: Precipitation Seasonality; BIO16: Precipitation of Wettest Quarter; BIO17: Precipitation of Driest Quarter; BIO18: Precipitation of Warmest Quarter; BIO19: Precipitation of Coldest Quarter. The symbol '**' indicates a significant correlation at the level of $\alpha = 0.01$.

1 **Table 1:**

2 **Pairwise Pearson's correlation coefficients of environmental variables.**

	BIO1	BIO2	BIO3	BIO4	BIO5	BIO6	BIO7	BIO8	BIO9	BIO10	BIO11	BIO12	BIO13	BIO14	BIO15	BIO16	BIO17	BIO18
BIO2	0.003																	
BIO3	0.452**	-0.342**																
BIO4	-0.473**	0.366**	-0.338**															
BIO5	0.151**	0.139**	0.143**	0.094**														
BIO6	0.554**	-0.187**	0.498**	-0.734**	.091**													
BIO7	-0.322**	0.387**	-0.426**	0.896**	.282**	-0.645**												
BIO8	0.134**	0.183**	0.262**	0.026**	.162**	0.137**	0.203**											
BIO9	0.578**	-0.225**	0.476**	-0.762**	.115**	0.703**	-0.678**	0.065**										
BIO10	0.368**	0.139**	0.262**	-0.028**	.337**	0.238**	0.149**	0.026**	0.248**									
BIO11	0.486**	-0.214**	0.523**	-0.758**	.010**	0.731**	-0.689**	0.152**	0.731**	0.175**								
BIO12	0.384**	0.127**	-0.171**	-0.595**	.115**	0.485**	-0.358**	0.182**	0.501**	0.195**	0.473**							
BIO13	0.142**	-0.066**	-0.263**	-0.576**	-.200**	0.390**	-0.592**	-0.170**	0.413**	-0.154**	0.424**	0.330**						
BIO14	0.352**	-0.062**	0.321**	-0.326**	.180**	0.335**	-0.278**	0.164**	0.304**	0.182**	0.372**	-0.131**	-0.186**					

BIO15	-0.077**	0.045**	-0.281**	0.110**	.040**	-0.114**	0.100**	0.010**	-0.124**	0.021**	-0.069**	0.027**	-0.041**	-0.076**				
BIO16	0.397**	0.070**	-0.106**	-0.573**	.096**	0.561**	-0.389**	0.204**	0.517**	0.204**	0.550**	0.564**	0.338**	-0.145**	0.010*			
BIO17	0.282**	-0.057**	-0.156**	-0.464**	.108**	0.386**	-0.380**	0.084**	0.412**	0.096**	0.429**	-0.112**	-0.014**	0.059**	-0.035**	-0.117**		
BIO18	0.416**	0.058**	-0.106**	-0.522**	.076**	0.517**	-0.341**	0.122**	0.471**	0.217**	0.483**	0.527**	0.286**	-0.156**	0.029**	0.643**	-0.112**	
BIO19	0.264**	-0.118**	-0.087**	-0.451**	.098**	0.398**	-0.366**	0.039**	0.411**	0.097**	0.422**	-0.131**	-0.002	0.025**	-0.061**	-0.128**	0.350**	-0.131**

Notes:

BIO1: Annual Mean Temperature; BIO2: Mean Diurnal Range; BIO3: Isothermality; BIO4: Temperature Seasonality; BIO5: Max Temperature of Warmest Month; BIO6: Min Temperature of Coldest Month; BIO7: Temperature Annual Range; BIO8: Mean Temperature of Wettest Quarter; BIO9: Mean Temperature of Driest Quarter; BIO10: Mean Temperature of Warmest Quarter; BIO11: Mean Temperature of Coldest Quarter; BIO12: Annual Precipitation; BIO13: Precipitation of Wettest Month; BIO14: Precipitation of Driest Month; BIO15: Precipitation Seasonality; BIO16: Precipitation of Wettest Quarter; BIO17: Precipitation of Driest Quarter; BIO18: Precipitation of Warmest Quarter; BIO19: Precipitation of Coldest Quarter. The symbol ‘**’ indicates a significant correlation at the level of $\alpha = 0.01$.

Table 2(on next page)

Percent contribution and cumulative contribution of the environmental variables to the Maxent model.

Table 2:
Percent contribution and cumulative contribution of the environmental variables to the Maxent model.

Environmental variables	Code	Percent contribution	Cumulative importance
Mean Temperature of Coldest Quarter	BIO11	33.7	33.7
Precipitation of warmest quarter	BIO18	32.6	66.3
Temperature seasonality	BIO4	23.2	89.5
Precipitation of driest month	BIO14	2.6	92.1
Precipitation seasonality	BIO15	1.6	93.7
Min Temperature of Coldest Month	BIO6	1.3	95
Precipitation of Wettest Quarter	BIO16	1.2	96.2
Mean Temperature of Warmest Quarter	BIO10	1.0	97.2
Precipitation of Driest Quarter	BIO17	0.6	97.8
Annual Mean Temperature	BIO1	0.5	98.3
Precipitation of Wettest Month	BIO13	0.3	98.6
Isothermality (BIO2/BIO7) (* 100)	BIO3	0.3	98.9
Mean Diurnal Range (Mean of monthly	BIO2	0.2	99.1
Precipitation of Coldest Quarter	BIO19	0.2	99.3
Mean Temperature of Wettest Quarter	BIO8	0.2	99.5
Max Temperature of Warmest Month	BIO5	0.2	99.7
Mean Temperature of Driest Quarter	BIO9	0.1	99.8
Altitude	Alt	0.1	99.9
Temperature Annual Range (BIO5-BIO6)	BIO7	0.1	100
Annual Precipitation	BIO12	0	100