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

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

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Background. Citrus huanglongbing is a destructive disease of citrus and a major threat to the citrus industry throughout the world. The disease accounts for substantial economic losses in China every year. *Diaphorina citri* Kuwayama is the only way that citrus Huanglongbing is spread under natural conditions in the field. 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 huanglongbing.

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

Results. Our results showed that the training data indicated a better forecast (AUC= 0.971). The highly suitable areas for *D. citri* in China are mainly concentrated to the south of the Yangtze River, and the total area is 129.13×104 km^2. The moderately suitable areas are distributed to the north of the most suitable areas, and the area is 44.81×104 km^2, with a narrower distribution than the most suitable area. The important environmental factors affecting the distribution of *D. citri* were mean temperature of coldest quarter, precipitation of wettest quarter, temperature seasonality, min temperature of coldest month, and mean diurnal range. These results provide a valuable theoretical basis for risk zoning 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. The contribution rate of mean temperature of coldest quarter was the highest, indicating that it is most closely related to the distribution of *D. citri*.

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Abstract

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Introduction

Diaphorina citri Kuwayama belongs to Homoptera Psyllidae and is a major pest of Rutaceae plants, including *Citrus reticulata* Blanco, *Citrus sinensis* Osbeck, *Citrus maxima* Merr, and *Murraya paniculata* Jacks (Liu, et al., 2018). It is one of the most important insect pests in the world. *D. citri* mainly damages the new buds and shoots of Rutaceae plants. Adults disperse on the leaves and buds to suck juice, whereas nymphs cluster on shoots, buds and young leaves to suck. 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 by the branches and leaves. However, compared with the direct feeding damage, the greatest harm of *D. citri* is the transmission of the pathogen Huanglongbing (Manjunath, et al., 2008; Fan, et al., 2010).

D. citri is the only way that citrus Huanglongbing is spread under natural conditions in the field. The process of transmission of Huanglongbing by *D. citri* occurs as follows: after feeding, the pathogen uses its oral needle to enter the intestine 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, the *D. citri* has the ability to transmit Huanglongbing (Pelz-Stelinski et al., 2010). Citrus Huanglongbing is a worldwide citrus disease, is the most harmful and destructive disease in the citrus industry and is known as citrus cancer. As early as the middle of the 18th Century, reports were made of citrus Huanglongbing in India. Reinking first reported on the occurrence of citrus Huanglongbing in China in the 1920s, and the disease spread rapidly in the southern citrus-producing areas of China. By the end of the 1970s, except for Guangdong, Guangxi, Fujian, and Taiwan, the disease occurred in Sichuan and Jiangxi. At present, 11 of the 19 provinces with citrus cultivation have been harmed by citrus Huanglongbing, and the affected area accounts for more than 80% of the total cultivated area of citrus (Fan, et al., 2009; Hu and Zhou, 2010; Chen, et al., 2013).

Meteorological factors are important environmental factors affecting the distribution, occurrence and development of pests and diseases. Under the background of climate warming, the areas suitable for pests and diseases are increasing, which leads to the expansion of their geographical distributions (Monteith, 2000). Temperature is one of the main factors that restricts the distribution of pests on the earth. Climate warming increases the chances for insects restricted by low temperature to spread to high altitudes. In recent years, with the increase of winter temperature caused by global warming, the population of *D. citri* has expanded significantly, and its geographical distribution has spread northward year by year, which has aggravated the spread speed and damage scope of Huanglongbing (Chen, et al., 2016). Considering the uniqueness of *D. citri* to transmit citrus Huanglongbing, 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 fewer distribution points (Elith, et al., 2006). The MaxEnt model has been widely used by scholars at home and abroad. Kumar *et al.* used MaxEnt to predict the invasion potential of an exotic pest (*Phenacoccus solenopsis*) in India (Kumar, et al., 2014). Penado *et al.* used MaxEnt to analyze climatically suitable areas for bumblebees in undersampled parts of the Iberian Peninsula (Penado, et al., 2016). López-Martínez *et al.* (2016) studied the environmental suitability for *Agrilus auroguttatus* in Mexico using MaxEnt. Lozier and Mills (2011) used the correlative niche modeling method MaxEnt to predict the geographic distribution of *Epiphyas postvittana* 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 Huanglongbing (Inoue, et al., 2009; Hijaz, et al., 2016; Arp, et al., 2017;Killiny, et al., 2017; Yu and Killiny, 2018); research on its geographical distribution prediction is relatively rare. To provide a theoretical basis for the prediction, risk assessments and effective control of *D. citri*, the MaxEnt model was used to map the potential distribution of *D. citri* in China under current climate scenarios, and the relationship between the distribution of *D. citri* and the environmental factors was elaborated in this paper.

Materials & Methods

Environmental variables and Species data

In this study, to analyze the climatic suitability regionalization of *D. citri* in China, we chose climatic factors and altitude factors as the initial environmental variables. Climate variables, as well as altitude data, were downloaded from the official website of WorldClim (Kuhn, et al., 2016)(Table S1). Multiple collinearity may exist between the environmental variables, which affects the model's evaluation of response relationships and contribution rates, which in turn affects the accuracy of the simulation. Therefore, appropriate analysis and multicollinearity tests were used to screen the environmental variables based on Worthington's (2016) method. The impact of various environmental factors on the distribution should be considered as comprehensively as possible, and the most relevant variable factors should be selected for prediction and evaluation. Finally, five variables were selected: Mean Diurnal Range (bio2), Temperature Seasonality (bio4), Min Temperature of Coldest Month (bio6), Mean Temperature of Coldest Quarter (bio11), and Precipitation of Wettest Quarter (bio16).

To obtain the occurrence records of *D. citri* in the world, we accessed two online databases, including the European and Mediterranean Plant Protection Organization (EPPO, https://www.eppo.int/) and the Global Biodiversity Information Facility (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 Jiang's (2018) method to filter the distribution records, we used Google Earth to proofread the latitude and longitude. In strict accordance with the requirements of MaxEnt, duplicate records, fuzzy records and neighboring records were removed. Finally, 164 valid records were retained for constructing the models (Fig. 1). Occurrence records were processed in Microsoft Excel and saved in the format "as.CSV."

Modeling method and statistical analysis

MaxEnt mines the relationship between a set of sample locations and a corresponding grid cell of climatic layers based on climatological resemblance and then assumes the probability of the presence of the species in other cells of the study area. MaxEnt software (Version 3.4.1) which is now open source, was downloaded from the website of the American Museum of Natural History (http://biodiversityinformatics.amnh.org/open_source/maxent/) (Kumar and Stohlgren, 2009); 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 of *D. citri* and 19 climatic variables into the MaxEnt software to create the initial model. In the initial model, the 'Random test percentage' was set as 25, and the '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 contribution and permutation contribution of the environmental variables by the Jackknife test to select key environmental variables for modeling. Finally, the occurrence points and key 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 value. The remaining model settings were set to the same as the initial model (Zhu, et al., 2018).

The file output by the MaxEnt model is in ASCII format, and it cannot be visually displayed on the map. "Conversion Tools" in ArcGIS was used to convert the file from 'ASCII' to 'Raster' format, and the "Extraction" function was used to extract the probability distribution map of *D. citri* in China. We reclassified the distribution threshold and divided the suitable area into 4 categories, displaying them in different colors according to Wang's method (Wang, et al., 2018). The specific description is shown in Table 1.

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

Results

Model performance

Fig. 2 shows the ROC curve of the initial model. The AUC values of the training data and the test data are 0.985 and 0.973, respectively. According to the evaluation criteria in 2.2, the accuracy of the initial model is "excellent". Fig. 3 shows the ROC curve of the final model. The results show that the mean AUC value of the 10 replicates was 0.971, indicating that the prediction result was "excellent" and proving that the model can be used to study the potential distribution simulation of kiwifruit in China. The above results proved that the model can be used to study the potential distribution simulation of *D. citri* in China.

Selection of the key environmental factors

MaxEnt is a mathematical model based on the principle of climate similarity; it is used to explore the correlation between geographical distribution and climatic factors. A choice of climatic factors is the key to determining the accuracy of the simulation. Therefore we screened the key environmental factors. The results show the percent contribution of mean temperature of coldest quarter, precipitation of wettest quarter, temperature seasonality, min temperature of coldest month, and mean diurnal range were 44.6%, 10.2%, 8.1%, 6.6%, and 5.2% respectively, and the cumulative sum was 74.7%, which was significantly higher than the residual climatic factors (Table 2). The correlation between the 5 environmental factors was calculated using the

Pearson's rank correlation to eliminate the influence of collinearity on the modeling process. If the absolute value of the correlation coefficient between two environmental variables is greater than 0.8, there is a strong correlation. The correlation coefficients among the 6 environmental factors were all less than 0.8 and were selected as the dominant variables in this study. On this basis, the MaxEnt model of the distribution of *D. citri* in China was reconstructed, and the accuracy of the simulation results was evaluated (Table 3).

The potential distribution of D. citri in China

Combining the selected environmental variables, the MaxEnt model was used to obtain the suitable index distribution map of *D. citri* in China. ArcGIS software was used to superimpose the index distribution map with China's administrative division map to obtain the suitability regionalization map of *D. citri* (Fig. 4 and Table 4).

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, Hainan, Taiwan, southern and central Zhejiang, eastern Yunnan, east-central Sichuan, most of Chongqing, and Hong Kong. The total area of the highly suitable area in China is 129.13×10^4 km^2, which occupied 13.45% of the area of the national territory. The moderately suitable areas are distributed to the north of the most suitable areas, mainly in most of Yunnan, northern Guizhou, southern Hubei, southern Sichuan, southern Anhui, southern Jiangsu, northern and central Zhejiang, and Shanghai. The total area of the moderately suitable area is 44.81×10^4 km^2, with a narrower distribution than the most suitable area. The total suitable area (the most suitable area and the moderately suitable area) is 173.95×10^4 km^2, accounting for 18.12% of China's total area.

Environmental factors affecting the existence of D. citri

The relationship between the presence probability of *D. citri* and ecological factors can be judged 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 0.5.

As shown in Fig. 5, when the mean temperature of coldest quarter (percent contribution 44.6%) is below 0.58°C, the presence probability of *D. citri* is lower than 0.5. With the increase of mean temperature of the coldest quarter, the probability of the presence of *D. citri* increased rapidly and reached its highest at 1°C. Then, the probability of presence rapidly decreases. When the mean temperature of coldest quarter reaches approximately 2.64°C, the probability of the presence of citrus psyllium falls below 0.5. Therefore, the suitable range of mean temperature of coldest quarter of *D. citri* is 0.58-2.64°C.

When the precipitation of wettest quarter (percent contribution 10.2%) is below 508.23 mm, the presence probability of *D. citri* is lower than 0.5. With the increase of precipitation of wettest quarter, the probability of the presence of *D. citri* increased rapidly and reached its highest at 710.72 mm. After that, the probability of presence slowly decreases. When precipitation of wettest quarter reaches approximately 2100.73 mm, the probability of the presence of *D. citri* falls below 0.5. Therefore, the suitable range of precipitation of wettest quarter of *D. citri* is 508.23—2100.73 mm.

The trends of presence probability with the variables mean diurnal range, temperature seasonality and min temperature of coldest month are similar to the above 2 variables but differ in the magnitude and speed of change, and the suitable range is 5.02—12.06℃, 26.47—813.57 and 0.13—2.09℃. respectively (Table 5).

Discussion

Selection and evaluation of MaxEnt model

MaxEnt is a mathematical model based on maximum entropy theory, which uses species distribution data and environmental data to analyze the distribution state of species when the entropy is maximum (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 analyzing 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 prediction accuracy in 16 models; Zhang et al. (2016) used four models, MaxEnt, GARP, BIOCLIM and DOMAIN, to predict the potential habitat of *Pomacea canaliculata* in China. The results showed that the simulation effect of MaxEnt model was significantly higher than that of other models. Therefore, MaxEnt was selected as a simulation software for use in predicting the potential distribution of the macaque ulcer pathogen in Sichuan and to analyze the impact of environmental variables on its distribution.

The 19 bioclimatic variables we selected for the initial model were from WorldClim. The research confirms that the autocorrelation among the environmental variables will introduce redundant information into the simulation, which will reduce the accuracy of the simulation. Therefore, in order to improve the accuracy of prediction, we use Zhang and Liu's (2017) method to select environmental variables by comparing the percentage contribution rate and correlation coefficien. Finally, five variables were obtained to reconstruct the model.

ROC curves are widely used in the evaluation of species distribution models. For example, Wang et al. (2017) used ROC curves to evaluate the predictive effect of MaxEnt model on suitable habitats of Colorado potato beetle at a global scale; Han et al. (2015) used ROC curves to determine the accuracy of niche models in predicting the suitable habitats of *Bursaphelenchus xylophilus* in China. Therefore, the ROC curve is used to evaluate the prediction accuracy of the MaxEnt model. The stability of the model is verified by 10 repeated AUC values. The average AUC value of 10 repetitions of the model is 0.971, which indicates that the simulation effect is good, and the results can be used in this study.

Predicting the distribution of *D. citri* in China

We used the "extraction" tool of ArcGIS software to obtain the suitable areas for the Citrus Psylla in China. According to previous research results, the suitable areas were divided into four grades: highly suitable areas, medium suitable areas, low suitability areas and uncomfortable areas, and the suitable areas of each grade were calculated. The result 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 129.13×10^4 km^2. The moderately suitable areas are distributed to the north of the most suitable areas, and the area is 44.81×10^4 km^2. The total suitable area (the most suitable area and the moderately suitable area) is 173.95×10^4 km^2, and accounts for 18.12% 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 northerly. This difference may be caused by different prediction models, species distribution data and environmental variables.

The distribution of *D. citri* in China was investigated by 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 provinces, but not in Chongqing and Hubei. 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. For the highly suitable areas where *D. citri* occurs, timely measures are needed to prevent the spread of this pest to other areas. The inspection and quarantine work should be strengthened to prevent the introduction of *D. citri* to potentially suitable distribution areas with suitable host and climatic conditions. High vigilance should be maintained at the areas designated as unsuitable for *D. citri*. Because of global warming, those areas currently designated as being of low suitability or unsuitable may eventually become suitable for *D. citri*.

Key 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 factors are an extremely important part of environmental factors. Under other conditions that are relatively consistent, meteorological factors will become a decisive factor for the epidemic or large-scale outbreak of pests and diseases (Monteith, 2000; Qin, et al., 2017). Temperature is the main environmental factor affecting the population growth and decline of *D. citri*.

In this paper, the importance of environmental variables was tested by the jackknife method. The results showed that the contribution rate of mean temperature of coldest quarter was the highest, indicating that it is most closely related to the distribution of *D. citri*. The response curve showed that the probability of the presence of *D. citri* was very low when mean temperature of coldest quarter was below 0.58℃, which indicates that extremely low temperature limits the distribution of *D. citri*. In India, Atwal et al. (1970) found that extremely low temperatures were not conducive to the development the population of *D. citri*. Low temperatures below 0℃ 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) pointed out that low temperature in winter was the main factor limiting population growth, geographical distribution and potential transmission of *D. citri*. These results are consistent with the results of this study. 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* depends 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 judge the relationship between them.

Limitations of this study

In this study, the occurrence data of *D. citri* mainly come from EPPO, GBIF, and the literature, and the usable data were much fewer than the available data. Among the distribution points obtained by Database and consulting the literature, the distribution points without clear latitude and longitude need to determine the relevant information through the coordinate positioning software, so there is inevitably a certain geographic error. Studies have shown that the more comprehensive the species distribution data, the higher the accuracy of the model simulation when using the niche model to simulate the geographical distribution of species. Therefore, the results of this study have certain limitations and shortcomings.

The environmental variables used in this study are from the World Climate Database, which is the average of data from 1950 to 2000. 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). The lack of climate data in the past 20 years may lead to a deviation from the actual situation. Therefore, to ensure more reliable prediction results, more comprehensive and accurate distribution data of *D. citri* should be used, and the corresponding missing climate data should be supplemented in the next step.

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*. The basic niche refers to the largest niche that is occupied by a species under the most ideal living conditions. The niche model only analyzes the influence of abiotic factors on species distribution, suggesting that the niche predicted by the model is wider than the actual niche occupied by *D. citri*. The results show that the distribution of *D. citri* is not only affected by climate but is also closely related to topographic characteristics, soil types, soil physical and chemical properties, and kiwifruit cultivation density. In the next step, consideration of the interaction between species and other biological factors expressed would improve the prediction effect of the model.

Figure Legends

Figure 1:
Spatial distribution of occurrence records of *D. citri.*
Figure 2:
ROC curve and AUC value for the initial model.
Figure 3:
ROC curve and AUC value for the reconstruction model.
Figure 4:
Potential suitable distribution of D. citri in China based on MaxEnt model.
SC (Sichuan), YN (Yunnan), GZ (Guizhou), CQ (Chongqing), HB (Hubei), HN (Hunan), GX (Guangxi), GD (Guangdong), JX (Jiangxi), FJ (Fujian), AH (Anhui), ZJ (Zhejiang), HaN (Hainan), TW (Taiwan).
Figure 5:
Response curves of environmental variables in MaxEnt models.

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Figure 1

Spatial distribution of occurrence records of *D. citri.*

Figure 2

ROC curve and AUC value for the initial model

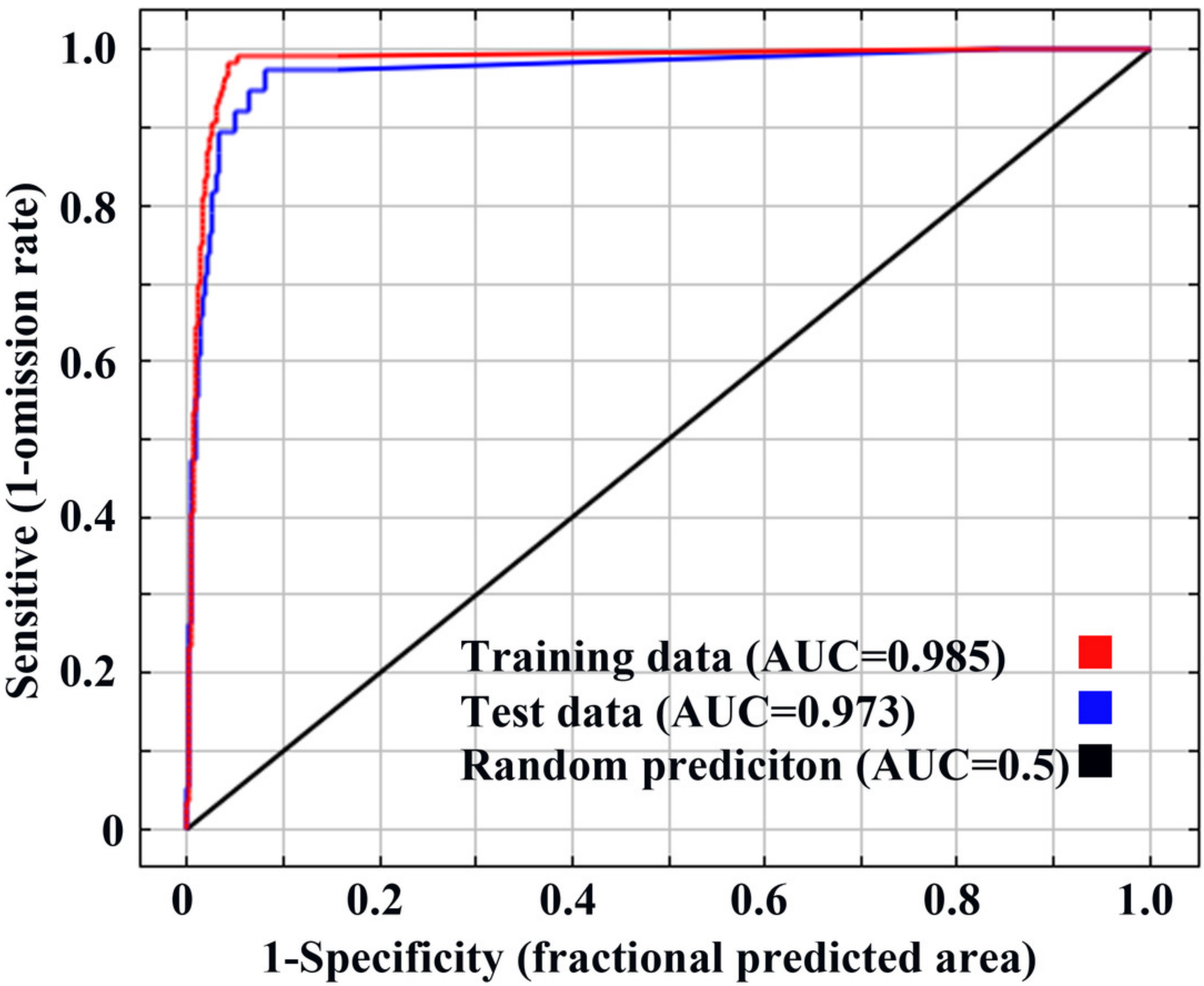

Figure 3

ROC curve and AUC value for the reconstruction model.

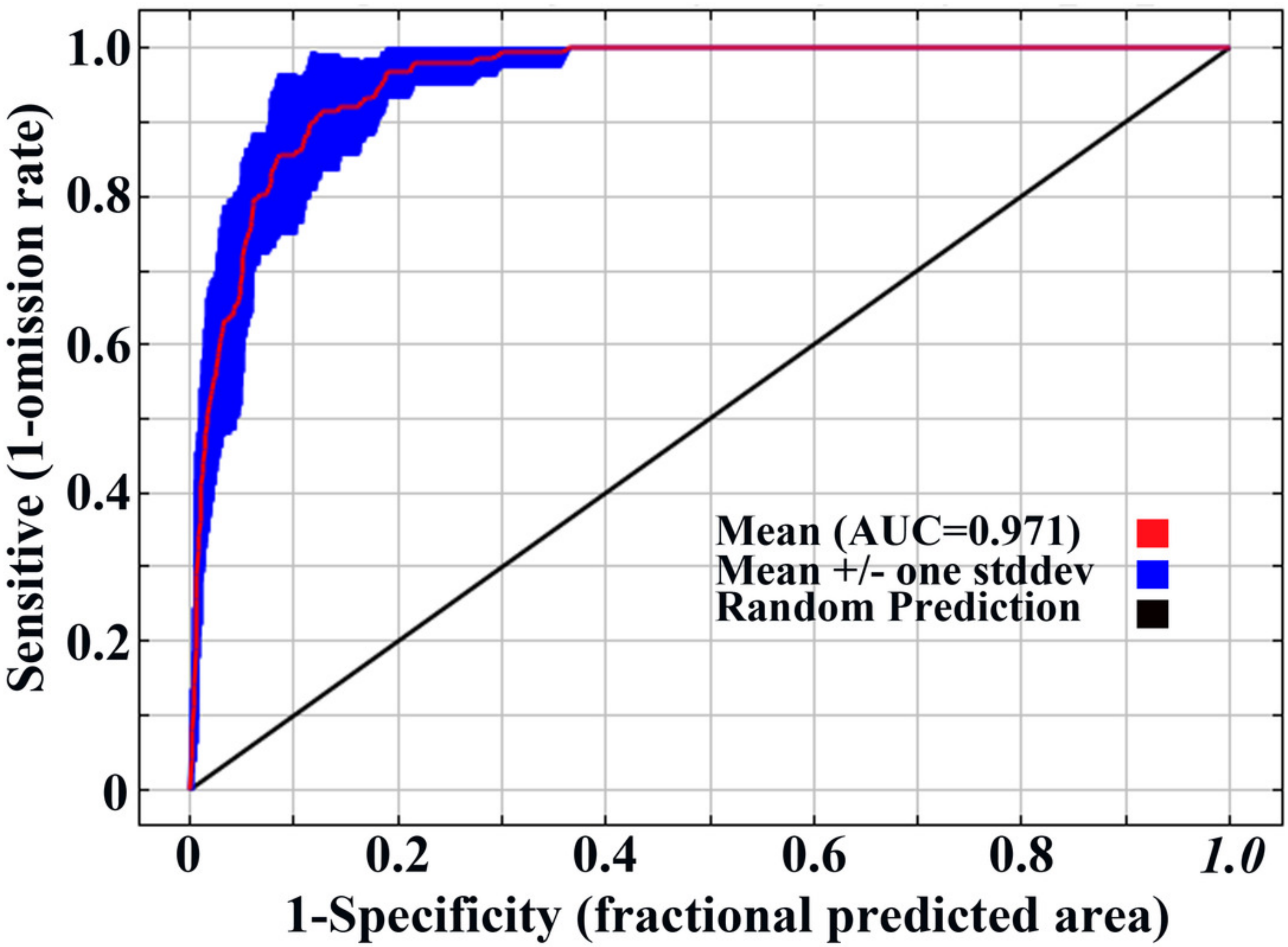

Figure 4

Potential suitable distribution of D. citri in China based on MaxEnt model.

SC (Sichuan), YN (Yunnan), GZ (Guizhou), CQ (Chongqing), HB (Hubei), HN (Hunan), GX (Guangxi), GD (Guangdong), JX (Jiangxi), FJ (Fujian), AH (Anhui), ZJ (Zhejiang), HaN (Hainan), TW (Taiwan).

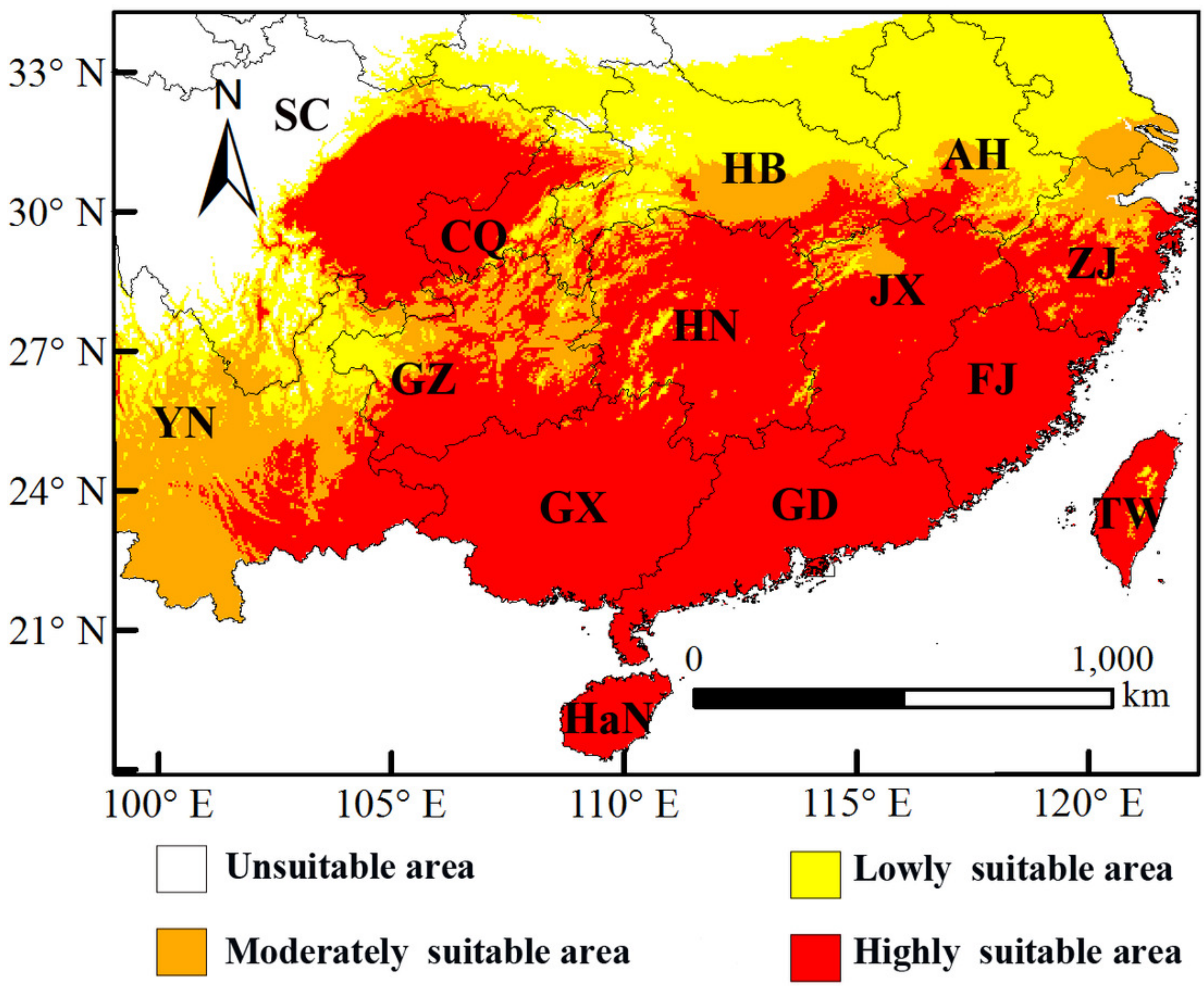

Figure 5

Response curves of environmental variables in MaxEnt models.

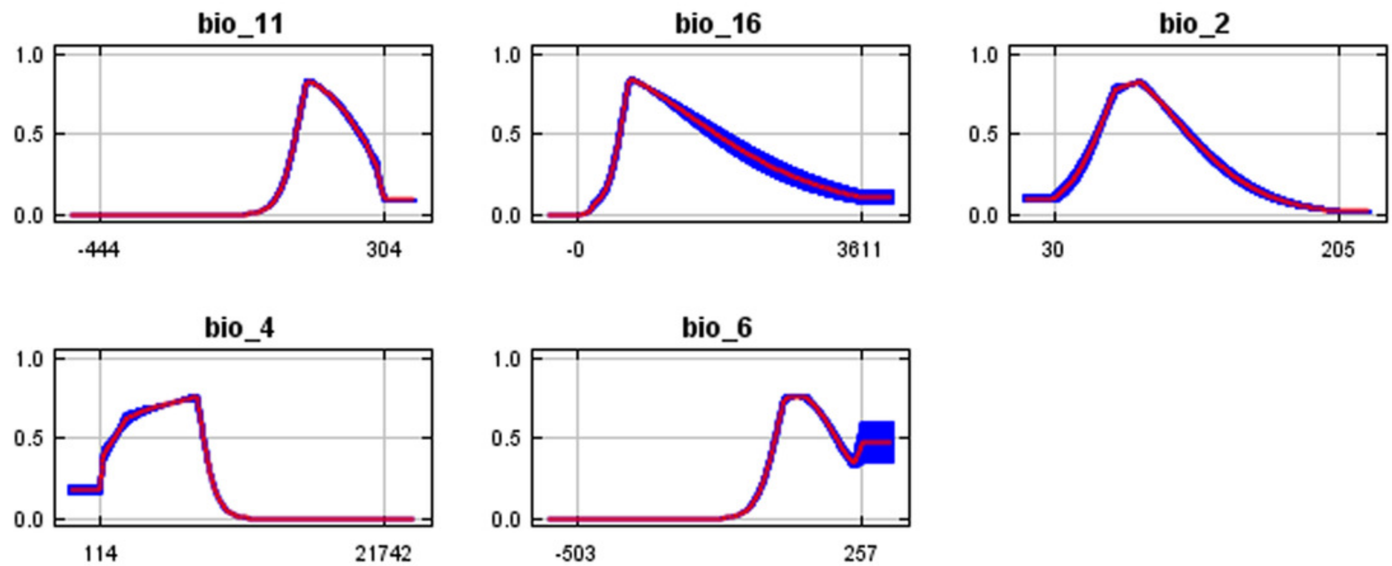

Table 1(on next page)

Standards of the probability in this research.

Table 1:

Standards of the probability in this research.

Habitat type	**Standards**	**Color**
Unsuitable area	$P \leq 0.05$	White
Lowly suitable area	$0.05 < P \leq 0.33$	Yellow
Moderately Suitable area	$0.33 < P \leq 0.66$	Orange
Highly suitable area	$P > 0.66$	Red

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	Percent contribution	Cumulative importance
Mean temperature of coldest quarter	44.6	44.6
Precipitation of wettest quarter	10.2	54.8
Temperature seasonality	8.1	62.9
Min temperature of coldest month	6.6	69.5
Mean diurnal range	5.2	76,7

Table 3 (on next page)

Pairwise Pearson's correlation coefficients of environmental variables.

bio2: Mean Diurnal Range; bio4: Temperature Seasonality; bio6: Min Temperature of Coldest Month; bio11: Mean Temperature of Coldest Quarter; bio16: Precipitation of Wettest Quarter. The symbol '**' indicates a significant correlation at the level of alpha = 0.01.

Table 3:

Pairwise Pearson's correlation coefficients of environmental variables.

Variables	bio2	bio4	bio6	bio11
bio4	0.057**			
bio6	0.086**	0.074**		
bio11	0.099**	0.081**	0.083**	
bio16	0.178**	0.079**	0.146**	0.142**

Notes:

bio2: Mean Diurnal Range; bio4: Temperature Seasonality; bio6: Min Temperature of Coldest Month; bio11: Mean Temperature of Coldest Quarter; bio16: Precipitation of Wettest Quarter. The symbol '**' indicates a significant correlation at the level of alpha = 0.01.

Table 4(on next page)

Predicted potential distribution areas for *D. citri* under current conditions.

Table 4:

Predicted potential distribution areas for *D. citri* under current conditions.

Provinces	**Area ($\times 10^4$ km^2)**			
	Unsuitable area	**Low suitability area**	**Moderately suitable area**	**Highly suitable area**
Guangxi	0.00	0.09	0.11	20.76
Hunan	0.00	0.66	2.13	16.60
Guangdong	0.01	0.00	0.00	15.60
Jiangxi	0.00	0.28	1.30	13.69
Sichuan	24.52	5.73	3.28	12.01
Fujian	0.01	0.00	0.05	10.93
Guizhou	0.00	1.48	5.43	9.05
Yunnan	2.29	6.08	18.19	7.72
Zhejiang	0.03	0.62	3.03	5.78
Chongqing	0.23	1.38	1.44	4.69
Taiwan	0.00	0.09	0.18	2.93
Hainan	0.01	0.00	0.00	2.91
Tibet	109.35	1.65	0.57	2.75
Hubei	0.60	9.48	5.10	2.39
Anhui	0.09	9.91	2.12	1.24
Hong Kong	0.00	0.00	0.00	0.09
Heilongjiang	54.44	0.00	0.00	0.00
Inner Mongolia	129.11	0.00	0.00	0.00
Xinjiang	175.62	0.00	0.00	0.00
Jilin	21.29	0.00	0.00	0.00
Liaoning	15.67	0.00	0.00	0.00
Gansu	40.79	0.73	0.01	0.00
Hebei	19.64	0.00	0.00	0.00
Beijing	1.72	0.00	0.00	0.00
Shanxi	15.96	0.00	0.00	0.00
Tianjin	1.22	0.00	0.00	0.00
Shaanxi	16.41	3.95	0.03	0.00
Ningxia	5.27	0.00	0.00	0.00
Qinghai	71.34	0.00	0.00	0.00

Shandong	14.05	1.35	0.00	0.00
Henan	9.70	6.43	0.00	0.00
Jiangsu	0.30	8.20	1.26	0.00
Shanghai	0.00	0.00	0.59	0.00
Macao	0.00	0.00	0.00	0.00
Total	729.67	58.09	44.81	129.13

Table 5(on next page)

The suitable range of dominant environmental variables affecting the potential distribution of *D. citri*

Table 5

The suitable range of dominant environmental variables affecting the potential distribution of *D. citri*

Environmental variables	Suitable range	Optimum value
Mean diurnal range (bio2)/℃	5.02—12.06	8.05
Temperature seasonality (bio4)	26.47—813.57	727.55
Min temperature of coldest month (bio6)	0.13—2.09	0.79
Mean temperature of coldest quarter (bio11)/℃	0.58—2.64	1
Precipitation of wettest quarter (bio16)/mm	508.23—2100.73	710.72