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Prediction of Potential Distribution of Red Imported Fire Ant in China Using the MaxEnt Model

Siyuan Wen [1*]

[1] South China Agricultural University, Guangzhou, 510000, China

Abstract. Solenopsis invicta Buren is a highly invasive and aggressive species. Since its invasion into China, it has rapidly spread to many regions, seriously threatening the local ecological balance and posing a huge threat to human life safety and agricultural production. To explore the suitable range of Solenopsis invicta Buren in China, this paper based on the distribution data obtained from GBIF database and the environmental factors obtained from the worldclim website to predict the potential geographical distribution of Solenopsis invicta Buren in China under historical climate conditions by MaxEnt model. The results show that the area under the ROC curves (AUC) of the training data is 0.967, which is reliable. Under the historical climate conditions, the potential suitable areas of Solenopsis invicta Buren in China are concentrated in Guangdong, Guangxi, Yunnan, Fujian, Hainan, Taiwan and other provinces. The mean temperature of coldest quarter (bio11) is the most important environmental factor affecting the suitable habitat of Solenopsis invicta Buren in China. The prediction can provide a scientific reference for monitoring the spread of Solenopsis invicta Buren and strengthening the prevention and control management.

1 Introduction

The red imported fire ant (RIFA), Solenopsis invicta Buren, is an omnivorous soil ant, belonging to Solenopsis, Formicidae, Hymenoptera. It has obvious harm to the natural environment, human health, agriculture and forestry, and is listed as one of the 100 most destructive species in the world by the World Conservation Union (IUCN) [1]. And it is a highly aggressive and invasive species in China and was listed in “The second batch of alien invasive species list” in 2010. RIFA was originally a species in South America, but through global trade, it has successfully invaded many regions, including the southern United States and Australia [2]. Its invasion has caused huge economic losses and ecological damage.

China has a wide range of international trade, which brings great pressure to the quarantine work. At the same time, because China has a vast area and a variety of ecosystems, which can provide habitat for a variety of organisms, it is extremely vulnerable to alien biological invasion. In 2004, RIFA was officially detected in Wuchuan, Guangdong Province for the first time in mainland China [3]. Since RIFA invasion, it has shown a significant ability of rapid propagation. Its scope extends from a single point to the vast areas of southern China, including dozens of provinces, cities and autonomous regions. At present, the distribution of RIFA in China is mainly concentrated in the Pearl River Delta and surrounding areas, and there is a trend of continuing to expand northward and westward [4], posing an escalating threat to national food security, ecological stability and public security.

Outside its native range, RIFA poses serious ecological threats due to its aggressive behavior. They are harmful to humans because of their powerful stings, which can cause allergic reactions, immediately cause severe itching or tingling, and appear blisters filled with pus. A few sensitive individuals may even have anaphylactic shock [5], which poses a serious threat to public health and safety. Moreover, it will affect the surrounding species. Due to the lack of natural enemies, it is easy to win the competition with local ants, thus damaging the ecological balance and endangering the local biodiversity. In addition, they may also damage the farmland environment, bite livestock, damage agricultural facilities, and cause huge economic losses to agricultural production.

Species distribution models (SDMs) are powerful tools for predicting the potential geographical distribution of species. Among them, the maximum entropy model (MaxEnt) is widely used because it can still show excellent performance when only the species occurrence point data is required [6]. By combining the known distribution point data of species with the environmental variable layer, the model estimates the niche demand of species, and then predicts the distribution probability of invasive species in different geographical spaces, and then predicts the potential geographical distribution of invasive species under historical and future climate conditions [7].

At present, although studies have used MaxEnt model to predict the suitable habitat of red imported fire ant in China [8], with the continuous updating of its distribution data, the refinement of environmental variable data and the continuous optimization of the

* Corresponding author: wensiyuan0931@outlook.com

model algorithm itself, it is necessary to carry out new and more accurate prediction research.

Therefore, the main purpose of this study is to integrate the historical official records and scientific literature, as well as the latest distribution records of red imported fire ant, simulate its current potential geographical distribution pattern in China by using MaxEnt model, optimize it by using ArcGIS software, and evaluate the limiting effect of key environmental variables on its distribution, so as to predict the diffusion process of RIFA in China, and provide some reference for preventing its further expansion.

2 Methods

2.1 GBIF Database Download Coordinates

The species distribution data of Solenopsis invicta in this study are mainly from the Global Biodiversity Information Facility (GBIF, https://www.gbif.org) and the list of administrative regions for the distribution of agricultural plant quarantine pests issued by the Ministry of agriculture and rural areas of China.

All available occurrence records of the red imported fire ant (Solenopsis invicta) were downloaded from the Global Biodiversity Information Facility (GBIF, https://www.gbif.org). The search was restricted to records from China (country code CN) collected between 2004 (the first detection year in mainland China) and 2025. Only records categorized as “human observation” or “preserved specimen” with valid geographic coordinates were retained, while fossil, automated, or suspicious records were excluded. The resulting dataset was exported as a CSV file for further processing.1.2 place supplement to the list of administrative regions for the distribution of agricultural plant quarantine pests in China.

At the same time, the information of all county-level administrative regions that recorded the occurrence of Solenopsis invicta from 2005 to 2025 was extracted from the official directory to check and supplement the location information. Following the collection of distribution data, this study subjected the downloaded coordinate points to quality control and standardisation procedures. First, duplicate records were removed using a composite key comprising species name + collection date + geographic coordinates, ensuring that the same event was not counted more than once. Second, missing or anomalous coordinate points were corrected or excluded through spatial validation using ArcGIS and Google Earth, thereby ensuring positional accuracy. All coordinate points were then uniformly projected into the WGS 84 coordinate system, providing a consistent basis for subsequent spatial analyses.

To reduce potential bias from relying on a single source, this study cross-referenced occurrence records at the county level with the Ministry of Agriculture and Rural Affairs’ official pest distribution catalogue. Spatial overlay analyses between GBIF records and the official catalogue were used to identify potentially omitted or misclassified areas. For administrative records without precise point locations, approximate coordinates were generated using the centroid substitution method. Although this approach cannot fully replace actual occurrence points, it effectively captures distribution patterns at a macro scale, making it suitable for ecological niche modelling and dispersal risk assessments.

Finally, to facilitate statistical and modelling analyses, all processed records were standardised into a tabular format that included collection date, geographic coordinates, administrative division, data source, and data type. After screening and supplementation, the final dataset exhibited both broad spatial coverage and strong temporal continuity, providing an accurate representation of the red imported fire ant’s spread across China. This dataset not only meets the requirements of the present study but also serves as a valuable reference for future risk assessments and management strategies related to invasive species.

2.2 Data Cleaning

The downloaded occurrence records of Solenopsis invicta were opened in Microsoft Excel for preprocessing. Only key fields, including species name, decimal longitude, decimal latitude, event date, country code, locality, and coordinate uncertainty (meters), were retained. Records with incorrect species names or outside China (country code $\neq$ CN) were removed. Entries with coordinate uncertainty greater than 5 km were excluded to ensure spatial accuracy. Duplicate points were identified and removed based on identical longitude–latitude combinations. After quality control, the cleaned dataset was saved as a new file for subsequent modeling analysis.

2.3 Environmental Variables Selection and Processing

Obtain the average values of 19 bioclimatic variables under historical conditions (1970-2000) from worldclim climate database. To avoid the impact of multicollinearity between variables on the prediction accuracy of the model, MaxEnt's own Jackknife method model was used to test the correlation of all bioclimatic variables [9]. Finally, six key environmental variables with high contribution rate were reserved for model construction. In the process of environmental variable processing, it is necessary to ensure that the selected variables can fully represent the climatic characteristics of the study area and avoid redundant information interfering with model performance. The 19 bioclimatic variables include temperature, precipitation and their seasonal indicators, which can reflect long-term climate patterns and potential ecological and environmental pressures. The Jackknife method of MaxEnt can be used to evaluate the contribution of each variable to the model, and the variables that are too correlated or have little impact on the prediction results can be eliminated to reduce the bias and instability caused by multicollinearity. The six key environmental variables retained in the final round have clear biological significance, such as temperature fluctuations, lowest temperatures in the coldest months, and annual precipitation, which can directly affect species distribution, ecosystem function, and environmental suitability analysis. During the variable processing process, it is necessary to unify the spatial resolution and projection to ensure the comparability of data from different sources on spatial and temporal scales, and at the same time imputation or smoothing of missing values to ensure the data integrity and continuity of the input model. In the model construction stage, the key environmental variables retained not only improve the prediction accuracy, but also provide a scientific basis for subsequent analysis, enabling research to more accurately assess the impact of environmental factors on ecosystems or species distribution, and provide quantitative reference for ecological management and policy formulation

2.4 MaxEnt Model Construction and Validation

Import the processed distribution data and environment variable data into MaxEnt software (version 3.4.1) for model training. 75% of the distribution points are randomly selected as the training set and 25% as the test set. The Bootstrap method is used to repeat the operation for 10 times, and the maximum number of iterations is 5000 [10]. The other parameters remain the default.

The area under the receiver operating characteristic curve (AUC value) was used to evaluate the performance of the model. AUC value greater than 0.7 indicates that the prediction result of the model is reliable, and greater than 0.9 indicates that the prediction accuracy is very high [11, 12].

2.5 Habitat Suitability Classification and Analysis

The distribution probability of MaxEnt output is visualized and reclassified using ArcGIS 10.8. The natural breakpoint method was used to divide the suitable areas into four levels: unsuitable areas, slightly suitable areas, moderately suitable areas and highly suitable areas [8]. By calculating the number of pixels at each level and counting their area, the spatial distribution pattern of the suitable habitat of Solenopsis invicta under historical climate conditions was analyzed. The habitat suitability classification analysis is based on the distribution probability map output by the MaxEnt model, which is visualized and re-graded by ArcGIS 10.8. The natural breakpoint method was used to divide the suitability into four levels: unsuitable zone, low suitable zone, medium suitable zone and high suitable zone. By stating the number of pixels of each grade and the area covered by them, the spatial distribution characteristics of different suitability levels in the study area can be quantified. This method can not only reveal the spatial pattern of potential habitats of Solensopsis invicta under historical climatic conditions, but also identify high-risk invasion areas and potential dispersal channels. Further analysis of the relationship between spatial distribution of suitability and environmental variables will help to understand the response mechanism of species to climate factors, and provide a scientific basis for ecological management, invasive species prevention and control, and resource allocation.

3 Literature References

Under historical climate conditions, the average AUC value of the prediction model for the potential geographical distribution of Solenopsis invicta in China is 0.967 after 10 predictions, indicating that the model has high reliability and can be used to predict the potential geographical distribution of Solenopsis invicta in China (Fig. 1).

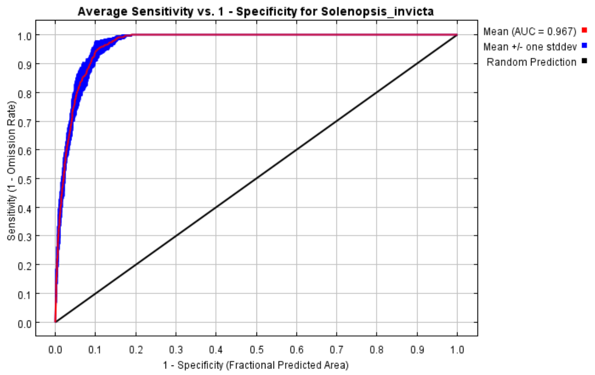

Fig. 1. ROC curves and AUC values of model MaxEnt for predicting the potential geographical distribution of Solenopsis invicta in China (Picture credit: Original)

After screening by Jackknife method, six key environmental variables with high correlation are retained, including: Mean temperature of coldest quarter (Bio11), Annual precipitation (Bio12), Precipitation of warmest quarter (Bio18), Mean temperature of wettest quarter (Bio8), Mean temperature of driest quarter (Bio9), Temperature seasonality (Bio4).

Among them, the contribution of mean temperature of cold quarter is the highest, and the contributions of other climate factors show that temperature and precipitation are important factors affecting the distribution of red imported fire ant (Fig.2).

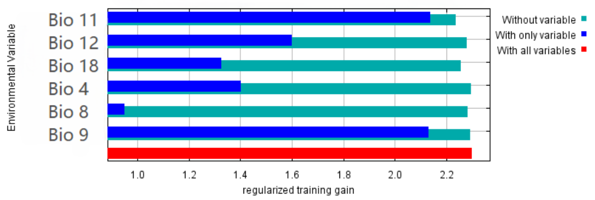

Fig. 2. Importance of six key environmental variables affecting potential geographical distribution of Solenopsis invicta in China (Picture credit: Original)

Under historical climate conditions, the main suitable areas of red imported fire ant are in southeast, southwest and southern China. The high fitness areas are concentrated in the southeast and south, including the southeast coastal area of Zhejiang Province, the southeast coastal and central sporadic areas of Fujian Province, the western and eastern coastal areas of Taiwan Province, the central and southern coastal areas of Guangdong Province and Guangxi Province, the northern coastal and central areas of Hainan Province, and the southern and Northern sporadic areas of Yunnan Province; The moderately suitable areas extend around the highly suitable areas, including central Fujian, northern Guangdong and Guangxi, Central Yunnan, Central Hainan, southern and Eastern Jiangxi, etc; The low suitable area extends to the surrounding areas, including Shanghai, sporadic areas in central Zhejiang Province, Northern Fujian Province, central Jiangxi Province, central Hunan Province, Northern Guangxi Province, Eastern Yunnan Province, the border between Chongqing and Sichuan Province, and a small part of the southern Tibetan Autonomous Region (Fig.3).

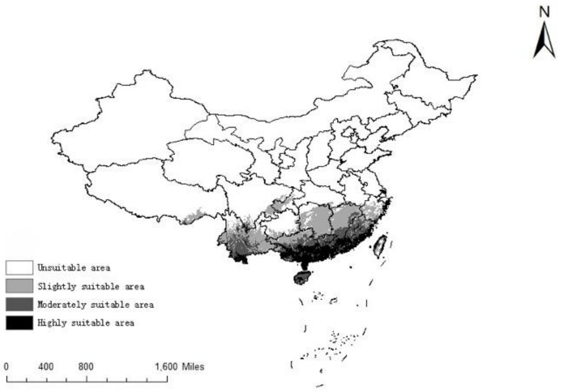

Fig. 3. Potential geographical distribution of Solenopsis invicta under historical climatic conditions (1970—2000) in China (Picture credit: Original)

The total suitable area of Solenopsis invicta in China is 1.28 × 106 km2, accounting for 13.33% of the total area in China, and the highly suitable area is 2.54 × 105 km2, accounting for 2.60% of the total area in China; The moderately suitable area is 3.38 × 105 km2, accounting for 3. 51%; The slightly suitable area is 6.90 × 105 km2, accounting for about 7.18%.

4 Conclusion

Based on the distribution data of Solenopsis invicta obtained from GBIF, this study used MaxEnt model to predict the potential geographical distribution of Solenopsis invicta in China under historical climate conditions. The dominant environmental variable selected in this study is mean temperature of cold quarter, indicating that its tolerance to low temperature is the key factor limiting its northward diffusion.

The results showed that the suitable areas of Solenopsis invicta were highly overlapped with important economic, agricultural and densely populated areas in China, and its invasion and colonization would pose a serious threat to China's agricultural and forestry production, public security and ecosystem. The results of this study have important management implications: first, as a traditional high fitness area, South China needs to continue to implement strict eradication and blockade measures to prevent its further spread. Secondly, the south of the Yangtze River, the Yangtze River Basin and the southwest, as moderately suitable areas and the main expansion areas in the future, should be listed as the frontier of key monitoring and control, strengthen quarantine and early eradication, and carry out forward-looking risk publicity and education to enhance the public and grass-roots awareness of prevention and control. It is suggested that relevant departments should formulate differentiated zoning management strategies according to the prediction results, strengthen quarantine supervision, monitoring and early warning and emergency extinguishing, to effectively curb the spread and harm of red imported fire ant, and ensure national biological safety, agricultural production and public health.

The limitation of this study is that it mainly considers the influence of climatic factors under historical conditions on its distribution but does not include the influence of non-climatic factors such as soil type, land use and human activities, which will also affect its distribution. At the same time, this analysis also does not consider the changes in suitable areas that may be caused by future climate conditions. In addition, species' adaptive evolution and interspecific competition may also change their actual distribution. Future research can integrate multi-source environmental data and consider biological interaction to further improve the prediction accuracy.

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