Pol. J. Environ. Stud. Vol. XX, No. X (XXXX), 1-12
DOI: *10.15244/pjoes/204193* ONLINE PUBLICATION DATE: 2025-06-04

Original Research

Prediction of the Potential Distribution Area for *Quercus acutissima* Carruth. in China under Climate Change

Nan Li[1, 2, 3#], Yuhao Li[1#], Jingyi Xie[1], Xingyu Chen[1], Xin Cheng[1], Jun Wang[1], Longwei Li[1, 2, 3*]

[1]School of Geographic Information and Tourism, Chuzhou University, Chuzhou 239000, China
[2]Anhui Province Key Laboratory of Physical Geographic Environment, Chuzhou University, Chuzhou 239000, China
[3]Anhui Engineering Research Center of Remote Sensing and Geoinformatics, Chuzhou University, Chuzhou 239000, China

Received: 10 March 2025
Accepted: 19 April 2025

Abstract

Quercus acutissima Carruth. is a crucial tree species in China's forest ecosystem, yet climate change poses a threat to its distribution. This study was designed to precisely predict its potential distribution area under varying climate scenarios. We gathered distribution points from multiple sources and environmental variables from relevant websites and models. After meticulous data processing and variable selection, a MaxEnt model was developed. Our research encompassed identifying the primary environmental factors influencing its distribution, analyzing the changes in potential suitable areas across different climate scenarios, determining climate-abnormal areas and their associated variables, and tracking the shift of the distribution center's gravity. The findings revealed that annual precipitation was the most significant environmental factor. Under current conditions, the total suitable area accounted for about 26% of the country's land area, with the highly suitable area approximately 25.6 km^2 (2.7% of the total area), the moderately suitable area about 109.9 km^2 (11% of the total area), and the low - suitable area around 115.2 km^2 (12% of the total area). Future climate scenarios demonstrated a northward expansion trend of suitable areas, with the SSP585 scenario showing the most prominent changes. The total suitable areas in the 2030s, 2050s, 2070s, and 2090s are approximately 293.23 km^2, 351.04 km^2, 393.07 km^2, and 462.14 km^2 respectively, showing an increase of 13.64%, 28.6%, 36.23%, and 45.76% respectively. The distribution center migrated northward over time. This study offers essential theoretical support for the protection, rational development, and utilization of *Q. acutissima* resources.

Keywords: *Quercus acutissima* Carruth., climate change, MaxEnt model, potential distribution area, environmental factors

*e-mail: lilw@chzu.edu.cn
#These authors contributed equally to this study and shared first authorship

Introduction

Quercus acutissima Carruth. is a deciduous tree species in the genus Quercus of the family Fagaceae, and it is one of the important tree species unique to China. It is widely distributed in the subtropical and temperate regions of China [1, 2]. Due to its strong adaptability and ecological functions, it occupies an indispensable position in the forest ecosystem. *Q. acutissima* has a well-developed root system, is drought-tolerant and able to grow in barren soil, and has a strong sprouting ability. It can be planted in mountainous areas, hilly areas, and uplands [3]. It is a pioneer tree species for barren mountains and wasteland, and an excellent tree species for soil and water conservation.

The wood of *Q. acutissima* is of excellent quality. Its mechanical properties, such as compressive strength along the grain, flexural elastic modulus, and flexural strength, belong to the medium-high-grade material level, and it has a wide range of uses. In addition, *Q. acutissima* grows fast, and the charcoal made from it has a high calorific value, produces no smoke, and has a high carbon content, making it an important raw material for high-quality charcoal.

However, with the continuous change of the global climate, key ecological factors such as temperature and precipitation are changing significantly, which has a profound impact on the living environment and distribution pattern of *Q. acutissima* [4-6]. Therefore, accurately predicting the potential distribution area of *Q. acutissima* under climate change is of great significance for formulating effective protection strategies, maintaining ecological balance, and promoting the sustainable development of forestry.

Species distribution models (SDMs) are tools for predicting species distribution. They infer the suitable areas for species by using the relationship between the current distribution of species and environmental variables. Currently, common species distribution models include the Generalized Additive Model (GAM) [7], the Genetic Algorithm for Rule - Set Prediction Model (GARP) [8], the Biological Climatic Model (BIOCLIM) [9], the Domain Model (DOMAIN), the Match Climate and Compare Location Model (CLIMEX) [10], the Ecological Niche Factor Analysis Model (ENFA) [10], the Classification and Regression Tree Model (CART) [11], and the Maximum Entropy Model (MaxEnt), etc.

The MaxEnt model can use species occurrence records and environmental variable data to effectively predict the potential distribution area of species. Compared with other models, it has the advantages of requiring fewer samples, being easy to operate, and having stable and accurate prediction results [12, 13]. The MaxEnt model has been widely applied in research such as predicting the potential distribution area of species, assessing the risk of invasive alien species, and studying the impact of climate change on species distribution areas and biodiversity [14-20].

At present, domestic and foreign research on *Q. acutissima* mainly focuses on its ecological characteristics and wood properties. However, there is a lack of reports regarding the potential suitable habitats, limiting factors, and possible responses of *Quercus acutissima* to future climate change in China. Therefore, based on the MaxEnt model, this study deeply analyzes the internal relationship between the current distribution pattern of *Q. acutissima* and climate factors, and predicts the change trend of the potential distribution area of *Q. acutissima* according to the future climate scenario data. Specifically, this study focuses on several key issues: What are the main environmental factors restricting the distribution of *Q. acutissima*? Under different climate scenarios, how will the area and geographical distribution pattern of the potential suitable areas of *Q. acutissima* change? In different climate scenarios, what are the climate-abnormal areas and the environmental variables with the highest degree of abnormality in the potentially suitable areas of *Q. acutissima*? How will the center of gravity of the potential suitable areas of *Q. acutissima* shift from the past to the future? The research on these issues is expected to provide a solid theoretical basis for the protection, rational development, and utilization of *Q. acutissima* resources, and contribute to forestry ecological construction and sustainable development.

Materials and Methods

Sample Point Data Collection and Processing

The distribution points of *Q. acutissima* were mainly obtained from the Global Biodiversity Information Facility (http://www.gbif.org/), Chinese Virtual Herbarium (https://www.cvh.ac.cn/), and National Specimen Information Infrastructure (http://www.nsii.org.cn/) (Fig. 1).

Environmental Variables and Processing

The bioclimatic variables (bio1-bio19) under the current climate were obtained from the WorldClim website (www.worldclim.org), representing average values from the years 1970 to 2000. The bioclimatic variables under four scenarios of future conditions (SSP126, SSP245, SSP370, and SSP585) were obtained from the Beijing Climate Center Climate System Model version 2 (BCC-CSM2). The model participated in CMIP6 historical test simulations and is better suited to the Chinese region. Each scenario was categorized into four periods: the 2030s (2021-2040), the 2050s (2040-2060), the 2070s (2060-2080), and the 2090s (2080-2100). In addition, topographic variables such as elevation, slope, and aspect were used for modeling. A total of 22 environmental variables were converted to ASCII format under ArcGIS 10.5.

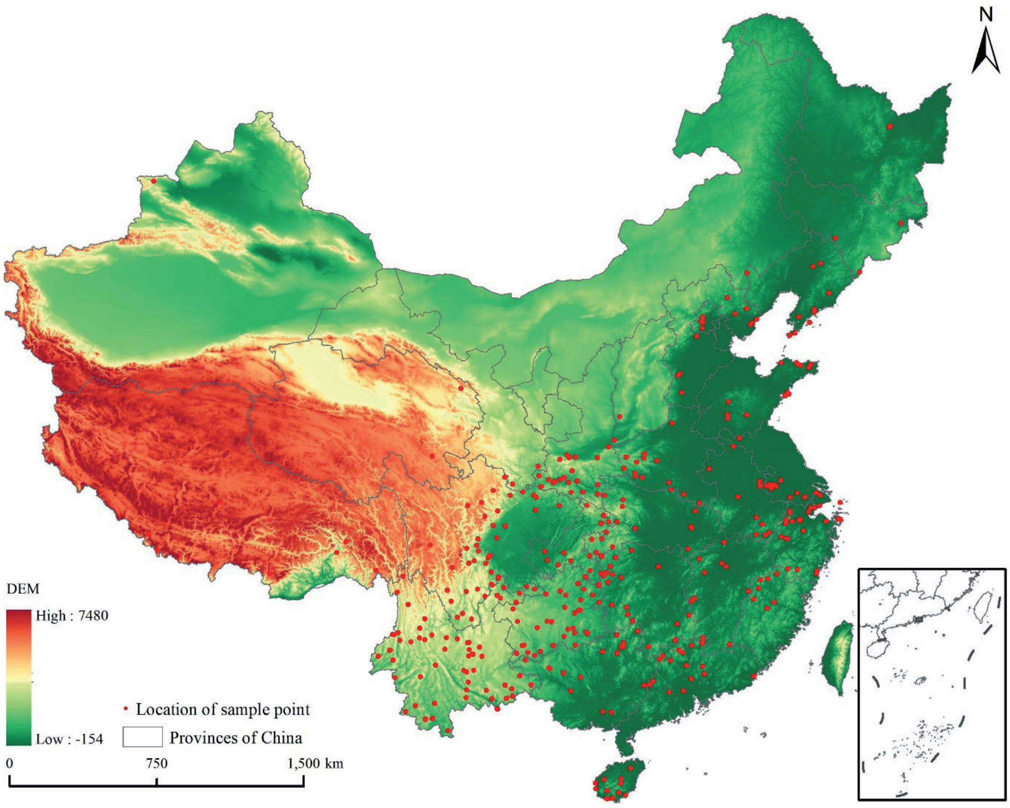

Fig. 1. Sample points of *Q. acutissima* in China.

Firstly, all the variables were analyzed by MaxEnt to get the contribution rate, and the correlation between the variables was obtained in SPSS. Then, variables with $|r| \geq 0.8$ and contribution rate less than 1 were excluded, and finally, 9 variables were kept. The 9 variables are bio2 (mean diurnal range), bio3 (isothermality), bio6 (minimum temperature of coldest month), bio7 (temperature annual range), bio12 (annual precipitation), bio14 (precipitation of driest month), bio15 (precipitation seasonality), slope, and aspect.

Model Construction and Evaluation

The MaxEnt model was constructed based on the sample points of *Q. acutissima* and environmental variables. Randomly select 75% of the species distribution points as training data, and the remaining points as test data. The cross-validation method was used to randomly divide the species distribution data into ten equal parts, one of which was arbitrarily selected as the test set, and the remaining nine as the training set, and the simulation was repeated for ten times, and the average of the results of the ten runs was taken as the output. The simulation results were output in logistic form. The area under curve (AUC) of the receiver operating characteristic curve (ROC) was calculated to evaluate the prediction accuracy of the model. The value of AUC is from 0 to 1, with the larger value indicating the higher credibility of the prediction results [21]. Based on the output of the MaxEnt model, the potential suitable areas of *Q. acutissima* were categorized into four levels: unsuitable area ($p<0.2$), low-suitable area ($0.2 \leq p<0.4$), medium-suitable area ($0.4 \leq p<0.6$), and high-suitable area ($p \leq 0.6$).

To provide a more intuitive and comprehensive understanding of the entire research process, especially the flow from data input to model construction and finally to result generation, we have created a research flowchart (Fig. 2). It serves as a visual guide, helping readers better follow the logical progression of our research and facilitating the understanding of the relationships between different components of the study.

Results

Analysis of Dominant Environmental Variables

In terms of the contribution of environmental variables, the top six environmental factors were bio12 (38.7%), bio6 (15.1%), bio14 (13.7%), slope (7.5%), bio3 (4%), and bio2 (2.7%), with a cumulative contribution of 81.7%. From the perspective of importance value, the top six environmental factors were bio12 (45.4%), bio7 (10.7%), slope (6.4%), bio3 (5.7%), bio2 (2.6%), bio15 (2.4%), with a cumulative importance value of 73.2%. Among them, the contribution and importance of bio12 were significantly higher than those of other environmental factors, indicating that annual precipitation is the most important environmental factor

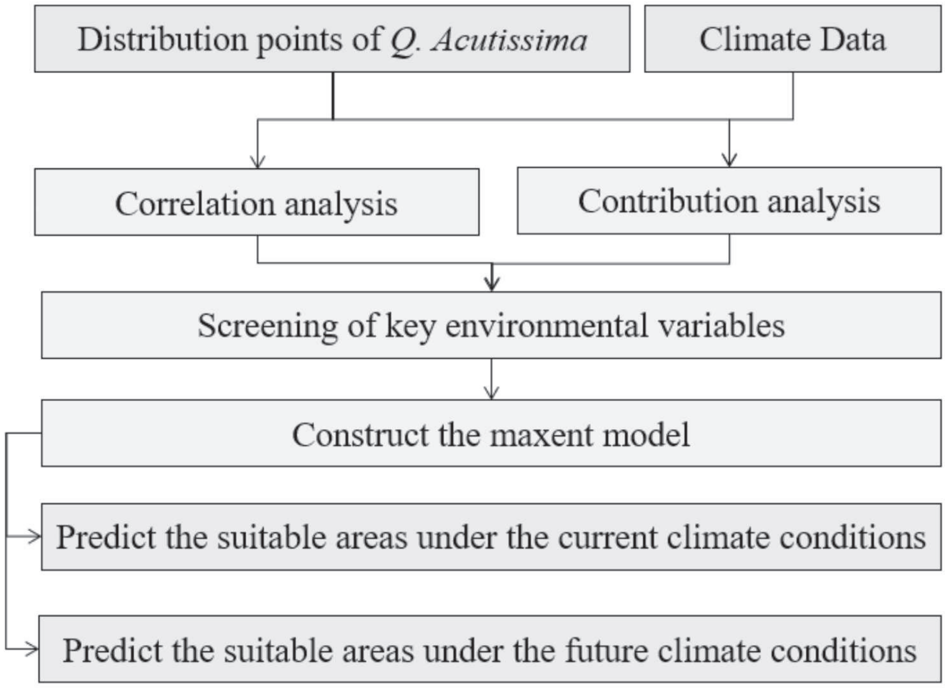

Fig. 2. Flowchart of the study.

influencing the potential geographic distribution of *Q. acutissima.* The response curve reflects the dependence of *Q. acutissima* on environmental variables. The single-factor response curve was plotted according to the modeling results, as shown in Fig. 3.

The environmental response curves of the MaxEnt model quantify the environmental variables. As can be seen from Fig. 3, when the annual precipitation (bio12) is between 400-1200 mm, the probability of the existence of *Q. acutissima* rises rapidly. After reaching the peak value (>0.6), it decreases with the increase of precipitation and remains stable after reaching 3200 mm. When the minimum temperature of the coldest month (bio6) is below -25ºC, the probability of the existence of *Q. acutissima* approaches 0. As the temperature rises, the probability of existence increases rapidly, decreases after reaching 5ºC, rises again when reaching 14ºC, slightly decreases after reaching the peak value (>0.8), and then tends to be stable. When the precipitation in the driest quarter (bio14) is between 0-20 mm, the probability of existence increases rapidly, decreases with the increase of precipitation after reaching the peak value (>0.6), and tends to be stable after the precipitation reaches 170 mm. Within different slope ranges, the probability of the existence of *Q. acutissima* is above 0.4. The lower the slope is, the (slightly) higher the probability will be. When the isothermality (bio3) is less than 20, the probability of existence is at a relatively high value and is relatively stable, with a specific value exceeding 0.8. When the isothermality is greater than 20, the probability of existence shows a significant downward trend. When the isothermality reaches 23, the probability of existence rises again and then decreases again. After the isothermality reaches 35, the probability of existence tends to be stable. When the isothermality reaches 38, the probability of existence rises again, and gradually tends to be stable after reaching the peak value of 0.89. When the average daily temperature range is between 4-5ºC, the probability of existence remains stable. Then the probability of existence increases with the increase of the daily temperature range difference, and gradually decreases after reaching the peak value. After the daily temperature range reaches 16ºC, the probability of existence gradually approaches 0. When the precipitation seasonality (bio15) is below 30, the probability of existence remains stable, and then increases with the increase of precipitation seasonality. When the probability of existence reaches 0.65, it decreases with the increase of precipitation seasonality. When the precipitation seasonality reaches 120, the probability of existence reaches the minimum value, then rises again, and tends to be stable after reaching the peak value (>0.8). When the aspect is less than 0, the probability of the existence of *Q. acutissima* also approaches 0. As the aspect increases, the probability of existence rises rapidly, slightly decreases after reaching the peak value, and then remains stable. After the aspect reaches 350, the probability of existence decreases and remains stable after dropping below 0.4. When the annual temperature range (bio7) is below 15ºC, the probability of existence is at the peak value and remains stable. After the annual temperature range is greater than 15ºC, the probability of existence gradually decreases and tends to be stable after reaching 0.6%. As the annual temperature range continues to rise, the probability of existence decreases

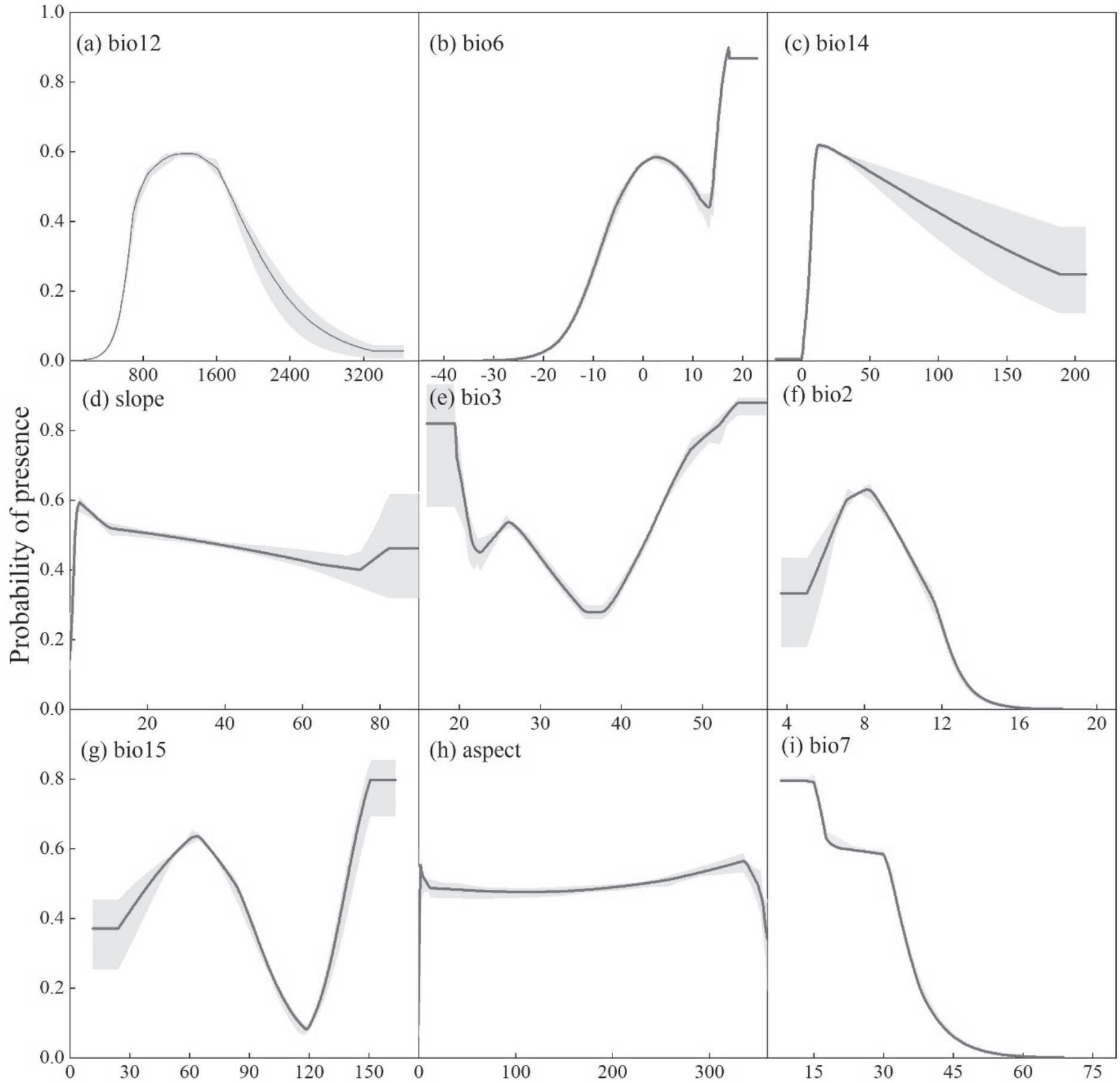

Fig. 3. MaxEnt model environmental response curves for key variables.

again. After the annual temperature range reaches above 55, the probability of existence gradually approaches 0.

Spatial Distribution of Suitable Areas for *Q. acutissima* under Current Climate Conditions

The suitable areas for *Q. acutissima* are shown in Fig. 4, and the distribution areas and proportions of each suitable area are presented in Table 2. Under the current climate situation, the total suitable area for *Q. acutissima* in China is 250.7 km^2, accounting for approximately 26% of the total land area of the country. The distribution of suitable areas is relatively concentrated, mainly in the central and southeastern coastal regions. The highly suitable areas are mainly distributed in regions such as Yunnan, Hubei, and Sichuan, with an area of approximately 25.6 km^2, accounting for 2.7% of the total area. The moderately suitable areas are mainly distributed in regions such as Jiangxi, Hunan, and Guizhou, with an area of approximately 109.9 km^2, accounting for 11% of the total area. The low-suitable areas are mainly distributed in regions such as Fujian, Zhejiang, and Shanxi, with an area of approximately 115.2 km^2, accounting for 12% of the total area.

Spatial Distribution of Suitable Areas for *Q. acutissima* under Future Climate Change Scenarios

Based on the future climate variables, the MaxEnt model was established. The average AUC values of the results are all greater than 0.89 (Table 2), indicating a high model accuracy. The suitable distribution areas of *Q. acutissima* in China under the future climate scenarios are shown in Fig. 5. Under different SSP scenarios, the suitable distribution areas of

Table 1. Environmental variables used for modeling.

Factor Type	Code	Ecological Factor	Unit
Terrain factor	ele	Elevation	m
	slope	Slope	°
	aspect	Aspect	-
Climate factor	bio1	Annual Mean Temperature	ºC
	bio2	Mean Diurnal Range	ºC
	bio3	Isothermality	-
	bio4	Temperature Seasonality	-
	bio5	Max Temperature of Warmest Month	ºC
	bio6	Min Temperature of Coldest Month	ºC
	bio7	Temperature Annual Range	ºC
	bio8	Mean Temperature of Wettest Quarter	ºC
	bio9	Mean Temperature of Driest Quarter	ºC
	bio10	Mean Temperature of Warmest Quarter	ºC
	bio11	Mean Temperature of Coldest Quarter	ºC
	bio12	Annual Precipitation	mm
	bio13	Precipitation of Wettest Month	mm
	bio14	Precipitation of Driest Month	mm
	bio15	Precipitation Seasonality	-
	bio16	Precipitation of Wettest Quarter	mm
	bio17	Precipitation of Driest Quarter	mm
	bio18	Precipitation of Warmest Quarter	mm
	bio19	Precipitation of Coldest Quarter	mm

Q. acutissima show certain changing patterns over time. In general, there is a trend of northward expansion in the suitable areas, and the areas and distribution ranges of each suitable area have also changed. Among them, the changes are the most significant under the SSP585 scenario. The highly suitable area and moderately suitable area expand significantly northward with a substantial increase in area, and the low suitable area almost covers most parts of the country. The changes under the SSP126 scenario are relatively gentle.

Under the SSP126 scenario, the total suitable areas of *Q. acutissima* in the 2030s, 2050s, 2070s, and 2090s are approximately 285.92 km^2, 306.96 km^2, 295.82 km^2, and 298.32 km^2 respectively, representing an increase of 12.34%, 18.35%, 15.27%, and 15.98% compared with the same period. Under the SSP245 scenario, the total suitable areas of *Q. acutissima* in the 2030s, 2050s, 2070s, and 2090s are approximately 287.02 km^2, 318.34 km^2, 343.68 km^2, and 342.49 km^2 respectively, representing an increase of 12.67%, 21.26%, 27.07%, and 26.82% compared with the same period. Under the SSP370 scenario, the total suitable areas of *Q. acutissima* in the 2030s, 2050s, 2070s, and 2090s are approximately 293.25 km^2, 313.85 km^2, 362.47 km^2, and 405.86 km^2 respectively, representing an increase of 14.53%, 20.14%, 30.85%, and 38.24% compared with the same period. Under the SSP585 scenario, the total suitable areas of *Q. acutissima* in the 2030s, 2050s, 2070s, and 2090s are approximately 293.23 km^2, 351.04 km^2, 393.07 km^2, and 462.14 km^2 respectively, representing an increase of 13.64%, 28.6%, 36.23%, and 45.76% compared with the same period. Under the future climate scenarios, the unsuitable areas will decrease compared with the present, while the low suitable areas, moderately suitable areas, and total suitable areas will increase compared with the present.

Centroid Migration in the Suitable Area for *Q. acutissima* under Climate Change Scenarios

Under different climate conditions, the migration of the distribution center of the suitable areas for *Q. acutissima* in different periods is shown in Fig. 6.

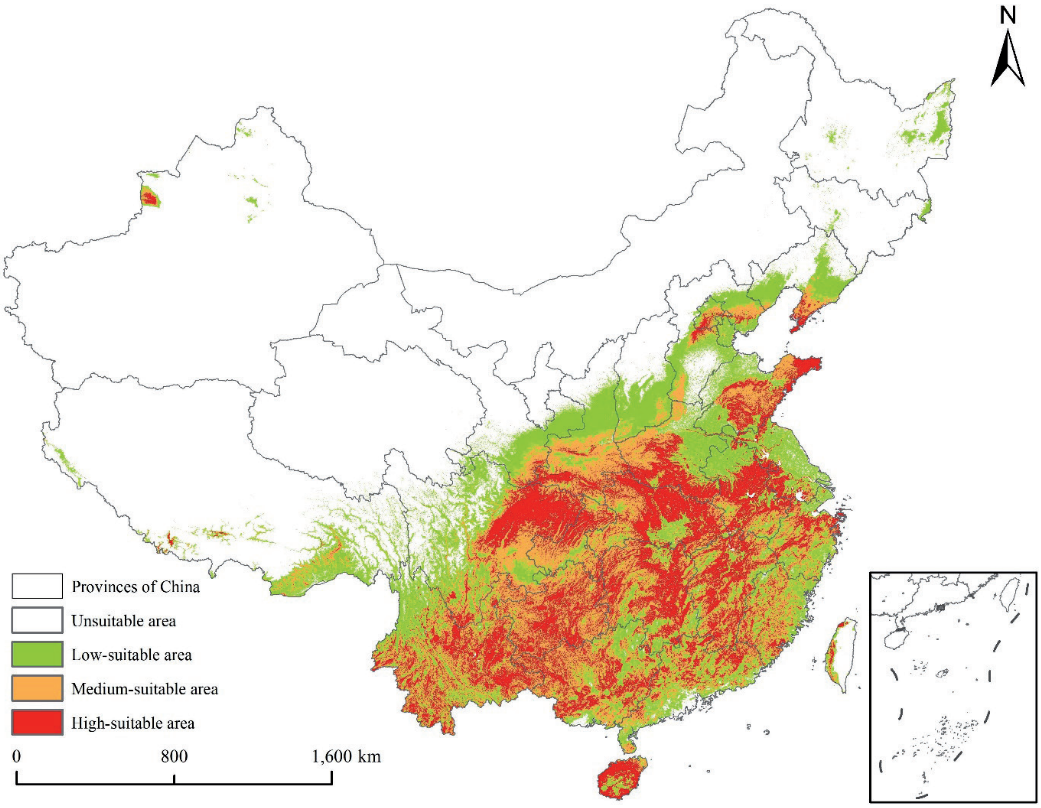

Fig. 4. Suitable areas for *Q. acutissima* in China under the current climate.

Table 2. Areas of *Q. acutissima* suitable areas under different climate scenarios.

Climate Scenarios Area (10^5 km^2)		UA		LA		MA		HA		AUC
		Rate (%)	Area (10^5 km^2)	Rate (%)	Area (10^5 km^2)	Rate (%)	Area (10^5 km^2)	Rate (%)		
Current		709.35	/	115.16	/	109.86	/	25.63	/	0.893
SSP126	2030s	674.08	-5.23	105.95	-8.69	127.97	14.15	52.00	50.70	0.891
	2050s	653.04	-8.62	110.38	-4.33	123.22	10.84	73.37	65.06	0.897
	2070s	664.18	-6.80	117.93	2.35	114.82	4.32	63.06	59.35	0.896
	2090s	661.68	-7.20	126.61	9.05	111.39	1.37	60.32	57.50	0.895
SSP245	2030s	672.98	-5.40	112.77	-2.12	125.97	12.79	48.28	46.91	0.891
	2050s	641.66	-10.55	119.15	3.35	130.53	15.84	68.65	62.66	0.898
	2070s	616.32	-15.09	125.58	8.30	133.88	17.94	84.21	69.56	0.897
	2090s	617.51	-14.87	113.79	-1.21	127.83	14.06	100.87	74.59	0.893
SSP370	2030s	666.75	-6.39	107.41	-7.21	130.33	15.71	55.51	53.82	0.895
	2050s	646.15	-9.78	118.48	2.81	118.40	7.21	76.97	66.70	0.896
	2070s	597.53	-18.71	125.10	7.95	131.31	16.34	106.05	75.83	0.898
	2090s	554.14	-28.01	151.64	24.06	142.41	22.85	111.82	77.08	0.894
SSP585	2030s	669.77	-5.91	119.51	3.64	120.28	8.67	50.44	49.18	0.900
	2050s	608.96	-16.49	136.20	15.45	140.53	21.82	74.32	65.51	0.895
	2070s	566.93	-25.12	153.83	25.14	144.98	24.23	94.26	72.81	0.893
	2090s	497.86	-42.48	159.20	27.67	176.11	37.62	126.83	79.79	0.901

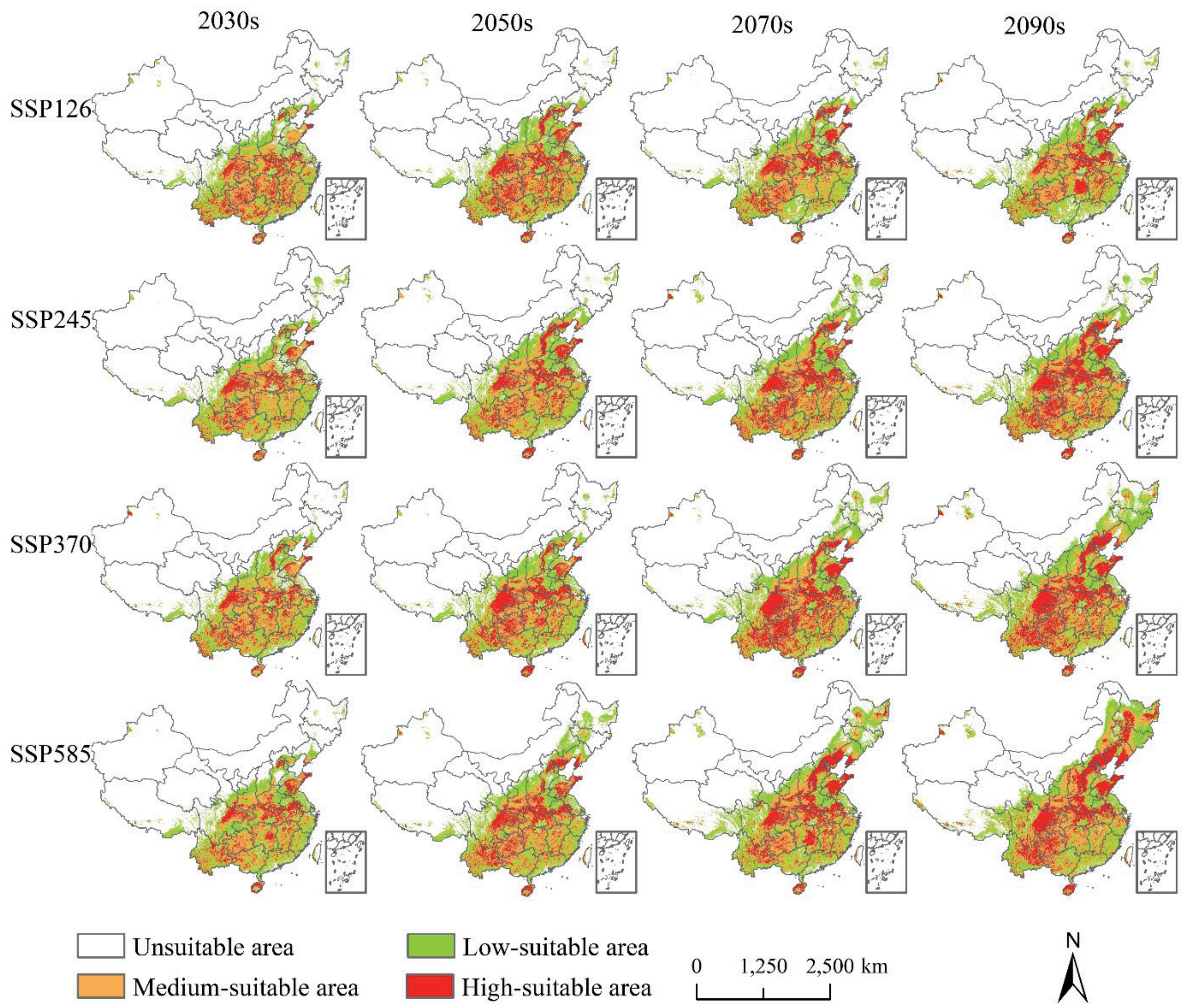

Fig. 5. Suitable areas for *Q. acutissima* in China under future climate.

Under the current climate conditions, the center is located in Zhangjiajie City in the northwestern part of Hunan Province (110.25ºE, 28.93ºN). Under the future SSP126 scenario, the center moves northeast in the 2030s (110.81ºE, 29.61ºN), and then moves northwest in the 2050s (110.74ºE, 29.85ºN). In the 2070s, it moves in the northwest direction (110.47ºE, 29.89ºN), and in the 2090s, it migrates in the northeast direction (110.99ºE, 30.12ºN). The distribution center moves from Hunan Province to Hubei Province. Under the SSP245 scenario, the center moves northeast in the 2030s (111.35ºE, 30.11ºN), and then moves northwest in the 2050s (110.97ºE, 30.27ºN). In the 2070s, it moves in the northeast direction (111.57ºE, 30.92ºN), and in the 2090s, it moves southwest (110.73ºE, 30.29ºN), migrating from Hunan Province to Hubei Province. Under the SSP370 scenario, the center moves northeast in the 2030s (110.86ºE, 29.9ºN), and then moves southwest in the 2050s (111.59ºE, 32.09ºN). In the 2070s and 2090s, it keeps moving north and finally reaches the northern part of Hubei Province (110.73ºE, 30.29ºN), migrating from Hunan Province to Hubei Province. Under the SSP585 scenario, the center moves north all the way. In the 2050s, it moves from Hunan Province to Hubei Province, and in the 2090s, it moves to Henan Province (111.88ºE, 32.57ºN).

Discussion

Main Environmental Factors Affecting the Distribution of *Q. acutissima*

Annual precipitation (bio12) emerged as the dominant environmental factor influencing *Q. acutissima*'s distribution, with a high contribution rate and importance value. This corroborates prior studies on other tree species where precipitation played a crucial role in determining suitable habitats. The response curve of bio12 indicates an optimal precipitation range of 400-1200 mm for *Q. acutissima*'s existence probability to peak. This could be attributed to the tree's physiological requirements for water during growth,

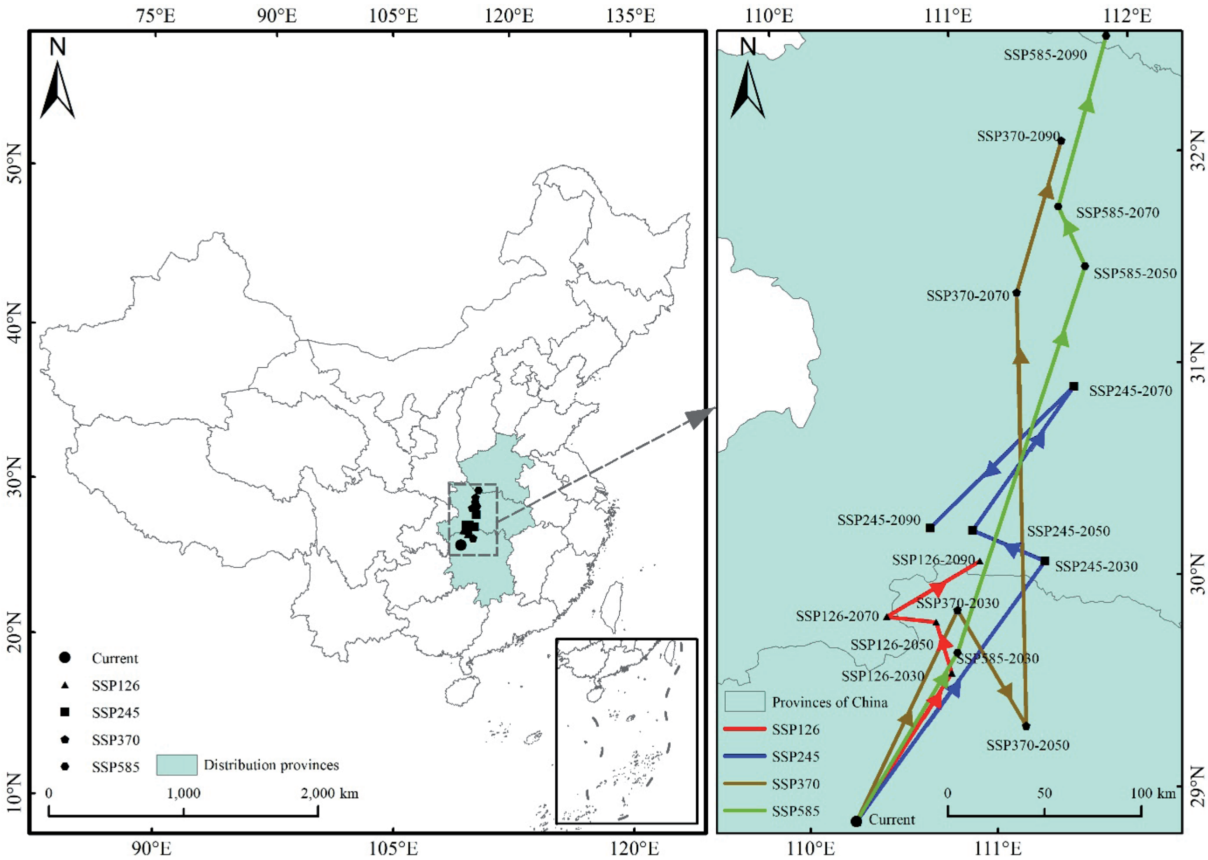

Fig. 6. Changes in geographical distribution of centroids in potential suitable areas for A under different climate scenarios.

germination, and reproduction processes. Adequate precipitation ensures proper photosynthesis, nutrient uptake, and turgor pressure maintenance in cells.

The minimum temperature of the coldest month (bio6) also significantly impacts distribution. Temperatures below -25ºC pose a severe threat to the species' survival, likely due to the risk of frost damage to cells and tissues, disrupting metabolic processes. As temperature rises within a certain range, the existence probability increases, but it decreases after reaching 5ºC and shows fluctuations thereafter. This implies that *Q. acutissima* has adapted to specific temperature thresholds and variations, with its physiological mechanisms fine-tuned to respond to temperature changes. Annual precipitation (bio12) stands out as the most critical environmental factor dictating the distribution of *Q. acutissima*, with its substantial contribution rate and importance value. The response curve of bio12 reveals that when the annual precipitation lies between 400-1200 mm, the probability of *Q. acutissima*'s presence surges and reaches its peak. This is because water is essential for the tree's physiological processes, such as photosynthesis, nutrient transportation, and maintaining cell turgidity during its growth and development stages. Adequate precipitation ensures the normal operation of these processes, thereby facilitating the survival and reproduction of *Q. acutissima*.

The precipitation of the driest month (bio14) also exerts a significant influence. When the precipitation in the driest month is within the range of 0-20 mm, the existence probability of *Q. acutissima* ascends rapidly. This indicates that *Q. acutissima* has a certain tolerance to dry conditions during this period. However, as the precipitation increases beyond the peak value (>0.6), the probability tends to decline and stabilizes when it reaches 170 mm. This suggests that excessive precipitation in the driest month might lead to waterlogging or other adverse effects, affecting the species' survival. It could be related to the root system's oxygen supply being affected by excessive soil moisture or the alteration of soil nutrient availability under such conditions.

The mean diurnal range (bio2) is another factor worthy of attention. When the average daily temperature range is between 4-5ºC, the probability of *Q. acutissima*'s existence remains relatively stable. Subsequently, as the daily temperature range difference expands, the probability initially increases and then gradually decreases after reaching the peak value. Once the daily temperature range exceeds 16ºC, the probability approaches zero. This implies that *Q. acutissima* has adapted to a specific temperature variation range. A moderate temperature variation might be beneficial for promoting certain physiological activities, like enhancing the tree's stress resistance. However, excessive temperature fluctuations could disrupt its metabolic balance and physiological functions, thus restricting its distribution.

The precipitation seasonality (bio15) also plays a role in determining the distribution. When the precipitation seasonality is below 30, the probability of existence remains relatively stable. As it increases, the probability first rises until it reaches 0.65 and then declines. When the precipitation seasonality reaches 120, the probability hits the minimum value before rising again and stabilizing after reaching the peak value (>0.8). This indicates that *Q. acutissima* has adapted to a certain degree of precipitation seasonality variation. A relatively stable precipitation pattern within a certain range is favorable for its growth. However, extreme precipitation seasonality changes could pose challenges to its survival, such as periods of drought or excessive rainfall concentrated in specific seasons, which may affect the tree's water use efficiency and nutrient uptake rhythm.

To further evaluate the robustness of these findings, we compared our MaxEnt model results with the Random Forest (RF) model. For the influence of environmental variables, the RF model also identified annual precipitation as an important factor. In terms of variable-response relationships, the response curves generated by RF were smoother, suggesting a more continuous and less abrupt change in the probability of *Q. acutissima*'s existence with respect to precipitation changes. This comparison highlights the differences in how different models represent the relationships between environmental variables and species distribution, and emphasizes the need for a comprehensive understanding when interpreting model results.

Variation of Distribution of Potential Suitable Areas of *Q. acutissima*

Under future climate change scenarios, the northward expansion of *Q. acutissima*'s suitable areas indicates its potential to adapt to new climate conditions. The SSP585 scenario shows the most significant changes, suggesting that under high-emission scenarios, the shift in climate factors creates more favorable habitats in northern regions. This could be due to increased precipitation and temperature changes that fall within the species' adaptable range. However, such expansion also brings challenges. New habitats may have different ecological communities and soil conditions, potentially leading to competition with native species or difficulty in establishing stable populations due to soil nutrient imbalances.

The migration of the distribution center's gravity reflects the dynamic nature of *Q. acutissima*'s distribution in response to climate change. The movement from Hunan Province to Hubei Province and even further northward implies that conservation strategies need to be adjusted accordingly. Conservation efforts should not only focus on existing distribution areas but also consider potential new habitats. Monitoring and research in these newly emerging areas are essential to understand the species' adaptation process and to develop appropriate management measures. Additionally, the decrease in unsuitable areas and the increase in suitable areas call for a reassessment of land use planning in forestry and agriculture. For example, in regions where *Q. acutissima* is expected to expand, forestry plantations could be planned in advance to promote ecological restoration and economic development while ensuring the species' survival and growth.

Furthermore, the changes in potentially suitable areas also have implications for biodiversity. The expansion or contraction of *Q. acutissima*'s distribution may affect associated species in the ecosystem, such as insects, birds, and other plants that rely on it for food or habitat. Understanding these ecological interactions is crucial for maintaining overall ecosystem stability and biodiversity. Future research could focus on studying these complex ecological relationships and developing comprehensive conservation strategies that consider the entire ecosystem rather than just the target species.

Conclusions

This study represents a significant step forward in understanding the potential distribution of *Q. acutissima* under climate change. The key contributions are as follows: (1) We identified annual precipitation as the dominant factor influencing its distribution, along with other important factors like precipitation in the driest month, mean diurnal range, and precipitation seasonality. By analyzing their relationships with the species' existence probability through response curves, we gained a detailed understanding of its environmental requirements. (2) We accurately mapped the current suitable areas of *Q. acutissima* in China, which account for about 26% of the land area, and determined their regional distribution characteristics. We also predicted the northward expansion of suitable areas under future climate scenarios, with the SSP585 scenario showing the most significant changes, providing a basis for understanding the species' response to climate change. (3) We tracked the migration of the centroid of the suitable areas for *Q. acutissima* under different climate scenarios. This helps us understand the dynamic changes in its distribution and provides crucial information for adjusting conservation strategies and land-use planning. (4) Methodologically, we constructed a reliable MaxEnt model using multi-source distribution data and advanced model environmental variables. Through statistical analysis, we screened influential variables to improve the model's accuracy, offering a reference for similar studies on other tree species. (5) Our research provides essential theoretical support for the protection, rational development, and utilization of *Q. acutissima* resources. It also contributes to forestry ecological construction and sustainable development by guiding the formulation of conservation strategies and land-use plans in the context of climate change. Overall, our research fills the knowledge gap regarding *Q. acutissima*'s response to climate change in China and emphasizes the importance of integrating multi-source data and advanced modeling techniques in predicting species distribution changes.

In future research on *Quercus acutissima*, multiple directions are worth exploring. Firstly, it's crucial to study its complex ecological interactions with other species in the ecosystem, including how its distribution changes affect associated organisms, and analyze its ecological niche and relationships with other tree species for better forest ecosystem protection. Secondly, as the interactions among environmental factors are complex, advanced statistical methods like SEM should be used to comprehensively consider the effects of climate, topography, soil, etc., to accurately reveal the driving mechanisms of its distribution. Thirdly, with technological development, more precise and high-resolution data, combined with GIS technology, can improve model accuracy, and exploring or integrating advanced species distribution models can better simulate their distribution dynamics under different climate change scenarios. Finally, research on its adaptive strategies to climate change, including its physiological and ecological adaptability and the role of artificial interventions, as well as assessing genetic diversity among populations, is necessary for resource protection. Overall, our current research fills knowledge gaps and provides methodological references, and future research in these areas will further enhance understanding of its distribution and ecological functions, and support climate change response, forest ecosystem protection, and sustainable forestry development.

Acknowledgements

This research was funded by the Natural Science Research Project for Anhui Universities (Grant No. 2023AH030094, YQZD2024045, 2023AH051606, and 2022AH051111), Anhui Province Key Laboratory of Physical Geographic Environment (Grant No. 2022PGE004), and National College Student Innovation and Entrepreneurship Training Project (Grant No. 202410377014 and 202410377017).

Conflict of Interest

The authors declare no conflict of interest.

References

1. DENG W., WANG X., HU H., ZHU M., CHEN J., ZHANG S., CHENG C., ZHU Z., WU C., ZHU L. Variation characteristics of soil organic carbon storage and fractions with stand age in north subtropical *Quercus acutissima* Carruth. Forest in China. Forests. **13** (10), 1649, **2022**.
2. RUAN C., HU H., CHENG C., FANG P., JIA X., WU Z., ZHU L. Photosynthetic Processes and Light Response Model Fitting of *Quercus acutissima* Carruth. and Q*uercus variabilis* Bl. in the Changjiang River Delta, China. Forests. **13** (12), 2010, **2022**.
3. DINH T.T., AKAJI Y., MATSUMOTO T., TORIBUCHI T., MAKIMOTO T., HIROBE M., SAKAMOTO K. Sprouting capacity of *Quercus serrata* Thunb. and *Quercus acutissima* Carruth. after cutting canopy trees in an abandoned coppice forest. Journal of Forest Research. **23** (5), 287, **2018**.
4. YUAN S., SHI Y., ZHOU B., LIANG Y., CHEN X., AN Q., FAN Y., SHEN Z., INGVARSSON P.K., WANG B. Genomic vulnerability to climate change in *Quercus acutissima*, a dominant tree species in East Asian deciduous forests. Molecular Ecology. **32** (7), 1639, **2023**.
5. BHATTI U., YUHUAN YAN Y., ZHOU M., ALI S., HUSSAIN A., HUO Q. Time series analysis and forecasting of air pollution particulate matter ($PM_{2.5}$): an SARIMA and factor analysis approach. IEEE Access. **9**, 41019, **2021**.
6. BHATTI U., NIZAMANI M., HUANG M. Climate change threatens Pakistan's snow leopards. Science. **377**, 585, **2022**.
7. BECKER E.A., CARRETTA J.V., FORNEY K.A., BARLOW J., BRODIE S., HOOPES R., JACOX M.G., MAXWELL S.M., REDFERN J.V., SISSON N.B., WELCH H., HAZEN E.L. Performance evaluation of cetacean species distribution models developed using generalized additive models and boosted regression trees. Ecology and Evolution. **10** (12), 5759, **2020**.
8. PALFREYMAN J., CAMINADE C., GRAHAM-BROWN J., WILLIAMS D.J.L. Genetic Algorithm for rule – set prediction (GARP) model for *Phortica variegata* presence in the UK (version 2). Data in Brief. **17**, 268, **2017**.
9. XIE C., CHEN L., LI M., JIM C.Y., LIU D. BIOCLIM Modeling for Predicting Suitable Habitat for Endangered Tree *Tapiscia sinensis* (Tapisciaceae) in China. Forests. **14** (11), 2275, **2023**.
10. WU L.H., HILL M.P., THOMSON L.J., HOFFMANN A.A. Assessing the current and future biological control potential of Trichogramma ostriniae on its hosts Ostrinia furnacalis and Ostrinia nubilalis. Pest Management Science. **74** (6), 1305, **2018**.
11. LIU Y., LI C., SHAO H. Comparative Study of Potential Habitats for *Simulium qinghaiens*e (Diptera: Simuliidae) in the Huangshui River Basin, Qinghai–Tibet Plateau: An Analysis Using Four Ecological Niche Models and Optimized Approaches. Insects. **15** (2), 81, **2024**.
12. ELITH J., PHILLIPS S.J., HASTIE T., DUDÍK M., CHEE Y.E., YATES C.J. A statistical explanation of MaxEnt for ecologists. Diversity and Distributions. **17**, 43, **2010**.
13. PHILLIPS S.J., ANDERSON R.P., SCHAPIRE R.E. Maximum entropy modeling of species geographic distributions. Ecological Modelling. **190**, 231, **2006**.
14. YAN X., WANG S., DUAN Y., HAN J., HUANG D., ZHOU J. Current and future distribution of the deciduous shrub *Hydrangea macrophylla* in China estimated by MaxEnt. Ecology and Evolution. **11**, 16099, **2021**.
15. QI Y., PU X., LI Y., LI D., HUANG M., ZHENG X., GUO J., CHEN Z. Prediction of Suitable Distribution Area of Plateau pika (*Ochotona curzoniae*) in the Qinghai–Tibet Plateau under Shared Socioeconomic Pathways (SSPs). Sustainability. **14** (19), 12114, **2022**.

16. SHI X., WANG J., ZHANG L., CHEN S., ZHAO A., NING X., FAN G., WU N., ZHANG L., WANG Z. Prediction of the potentially suitable areas of *Litsea cubeba* in China based on future climate change using the optimized MaxEnt model. Ecological Indicators. **148**, 110093, **2023**.
17. WEI X., XU D., ZHUO Z. Predicting the Impact of Climate Change on the Geographical Distribution of Leaf hopper, *Cicadella viridis* in China through the MaxEnt Model. Insects. **14** (7), 586, **2023**.
18. LI S., WANG Z., ZHU Z., TAO Y., XIANG J. Predicting the potential suitable distribution area of *Emeia pseudosauteri* in Zhejiang Province based on the MaxEnt model. Scientific Reports. **13**, 1806, **2023**.
19. DU Z., XU W., WANG Y., YAN P., MA Z., HUANG G., LI H. Prediction of the potential distribution area of *Glycyrrhiza inflata* in China using a MaxEnt model. Frontiers in Ecology and Evolution. **12**, 1347066, **2024**.
20. UTOMO S.W., LESTARI F., ADIWIBOWO A., FATMAH., FISHER M.R., QADRIINA H.I. Predicting the suitable cultivation areas of breadfruit crops *Artocarpus altilis* (Moraceae) under future climate scenarios in Central Java, Indonesia. Frontiers in Plant Science. **15**, 1, **2024**.
21. CLAIRE A.Q., YOSHINORI N. Ecological niche modeling to determine potential niche of Vaccinia virus: a case only study. International Journal of Health Geographics. **16**, 28, **2017**.