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Article

Prediction of the Potential Distribution of *Teinopalpus aureus* Mell, 1923 (Lepidoptera, Papilionidae) in China Using Habitat Suitability Models

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Abstract: The Golden Kaiser-I-Hind (*Teinopalpus aureus* Mell, 1923) is the only butterfly among Class I national protected animals in China and is known as the national butterfly. In this study, by accurately predicting the suitable habitat in China under current and future climate scenarios, the potential distribution area of *T. aureus* was defined, providing a theoretical basis for conservation and management. Based on species distribution records, we utilized the Biomod2 platform to combine climate data from the BCC-CSM2-MR climate model, future shared socio-economic pathways, and altitude data. The potential distribution areas of *T. aureus* in the current (1970–2000s) and future SSP1_2.6 and SSP5_8.5 climate scenarios in China in 2041–2060 (2050s), 2061–2080 (2070s), and 2081–2100 (2090s) were predicted. The AUC and TSS values of the combined model based on five algorithms were greater than those of the single models, and the AUC value of the receiver operating characteristic curve was 0.990, indicating that the model had high reliability and accuracy. The screening of environmental variables showed that the habitat area of *T. aureus* in China was mainly affected by annual precipitation, precipitation in the driest month, the lowest temperature in the coldest month, temperature seasonality, elevation, and other factors. Under the current circumstances, the habitat area of *T. aureus* was mainly located in southern China, including Fujian, Guangdong, Guangxi, Hainan, Zhejiang, Yunnan, Guizhou, Hunan, Taiwan, and other provinces. The suitable area is approximately 138.95 $\times$ 10^4 km^2; among them, the highly suitable area of 34.43 $\times$ 10^4 km^2 is a priority area in urgent need of protection. Under both SSP1_2.6 and SSP5_8.5, the population centroid tended to shift southward in the 2050s and 2070s, and began to migrate northeast in the 2090s. Temperature, rainfall, and altitude influenced the distribution of *T. aureus*. In the two climate scenarios, the habitat area of *T. aureus* declined to different degrees, and the reduction was most obvious in the SSP5_8.5 scenario; climate was the most likely environmental variable to cause a change in the geographical distribution. Climate change will significantly affect the evolution and potential distribution of *T. aureus* in China and will increase the risk of extinction. Accordingly, it is necessary to strengthen protection and to implement active and effective measures to reduce the negative impact of climate change on *T. aureus*.

Keywords: *Teinopalpus aureus*; climate-suitable region; biomod2; ensemble model

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1. Introduction

Global climate change has significantly impacted species distributions, and analyzing the impact of climate change has become a major topic of research in various fields, including ecology [1,2]. According to the Sixth Assessment Report released by the Intergovernmental Panel on Climate Change (IPCC) in Interlaken, Switzerland, over the past century, the combustion of fossil fuels and unequal, unsustainable use of energy and land have led to a continuous rise in global temperatures, which are now 1.1 °C higher than pre-industrial levels [3]. This has led to more frequent and more intense extreme weather events, posing an increasingly serious threat to nature and humanity in every region of the world [4]. For insects, climate change can affect the overwintering survival rate, increase effective accumulated temperatures and the number of generations, and affect migration, dispersal, and distribution [5], while also reducing regional species diversity and further increasing the risk of species extinction [6].

To understand the specific environmental requirements of target species, species distribution models (SDMs) or ecological niche models are widely used. These models utilize statistical algorithms to simulate ranges in multidimensional environmental spaces, abstract ecological niches, or ranges into statistical rules, and simulate the potential distribution of suitable habitats for species in different spatial and temporal environments [6,7]. In recent years, with the development of statistical algorithms and niche species distribution models, dozens of distribution prediction models have been proposed in many studies, but their scope of application and theoretical algorithms vary. Since R released the biomod package in 2003, it has been widely recognized and used by biologists, and the combined model established based on R has a higher prediction accuracy for species distribution than that of a single model [8,9]. The updated biomod2 package has a good fit even with a small sample size (population) (<20) [10].

The Golden Kaiser-i-Hind (*Teinopalpus aureus* Mell, 1923) is a typical mountain butterfly species from the family Papilionidae [11]. It is distributed in subtropical and tropical regions of China, Vietnam, and Laos, limited to mountains with steep terrain and high forest coverage rate [12–14]. Owing to its rarity in the wild, the species has garnered significant attention from entomologists and conservation researchers worldwide. *T. aureus* is adapted to evergreen broad-leaved forests and is considered a habitat-specialized species. The confirmed host plants include a few species of magnolia trees, making it a relatively oligophagous insect. The egg and larval stages often live in the canopy of trees [15]. In the tropical rain forest of Hainan, this butterfly, like most lepidoptera insects, has the characteristics of year-round occurrence and overlapping generations [16]. Studies in Guangxi have shown that female butterflies mostly choose to lay eggs in the canopy of host plants that can be irradiated by sunlight. There are two generations per year and each female generally only lays one or two eggs on each host plant [15,17]. Due to the influence of habitat selection and human activities, the geographical population of the butterfly is limited to a few mountainous areas, and the habitat is distributed in an "island" shape [18]. In 1989, China included this butterfly in the national key protected wildlife list, making it the only butterfly species in China's first-level protected wildlife category [19]. In 2021, China included it in the "14th Five-Year Plan" for the development of forestry and grassland protection, making it the only insect species among the 48 wild animals in urgent need of rescue protection [20]. Although the conservation work of *T. aureus* has received high attention, the related research is still at a relatively basic stage, and no literature can provide information on the species richness of butterfly. As a result, it is difficult to obtain population occurrence data, and comprehensive information is lacking. To this day, the International Union for Conservation of Nature (IUCN) has listed this butterfly as "Data Deficient" [21].

Due to the limited historical occurrence data of the *T. aureus* and the need to improve the accuracy of models constructed based on a single algorithm [13], this study utilized the BCC-CSM2-MR climate model and future shared socio-economic pathways (SSPs) as climate data. By combining the geographical distribution and biological data of the *T. aureus*, the ensemble model (ESMs) by biomod2 [22] approach was employed to simulate the potential suitable habitat distribution of the butterfly in China. The aim was to predict the potential geographical distribution of the species with limited data in China with the ultimate goal of providing a theoretical basis for the conservation and management of the *T. aureus*. Therefore, the determination of the potential distribution changes under different climatic backgrounds in China can provide references for the future conservation of Papilio aureus in China.

2. Materials and Methods

A flow diagram showing the external data, analysis process, and derived data in the study is provided in Figure 1.

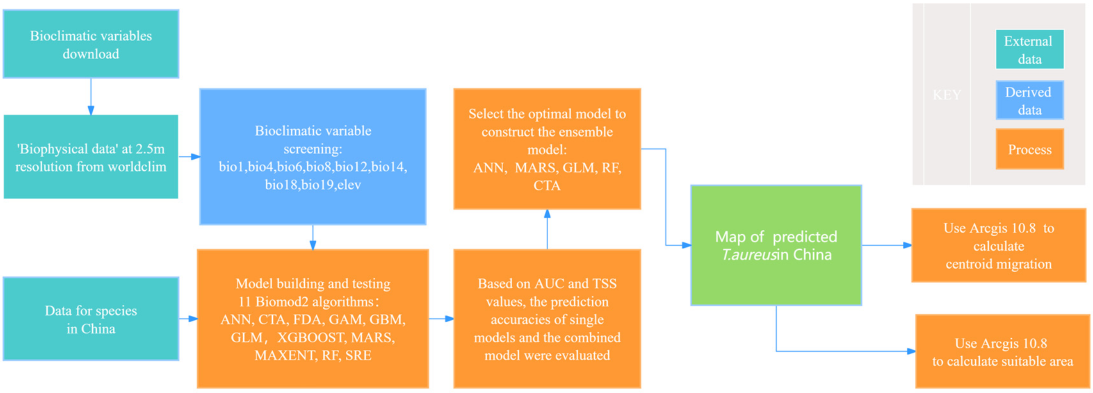

Figure 1. Schematic overview of the study with external data, derived data, and processes shown within the flow of information, processes shown within the flow of information.

2.1. Species Location Data

The geographical distribution data for *T. aureus* in China were mainly obtained from geographical coordinate records in the published literature (Table 1) and websites that record biological coordinate information, including the Global Biodiversity Information Network (GBIF, https://www.gbif.org/, accessed on 16 June 2023; *T. aureus*: https://doi.org/10.15468/dl.asuzc7, downloaded 19 July 2023), National Animal Specimens Repository (NACRC, http://museum.ioz.ac.cn/index.html/; accessed on 16 June 2023; *T. aureus*: http://museum.ioz.ac.cn/species_detail.aspx?id=22471; accessed on 16 June 2023). After removing some data with uncertain information or ambiguous names, as well as non-terrestrial and duplicate records, 57 valid distribution point coordinates were collected. To reduce the impact of spatial autocorrelation and sampling bias on the final prediction results, SDM Toolbox (version 2.5) was used for sparse data processing [10] to ensure that only one distribution point was retained in each 10 km × 10 km grid [23]; 42 occurrences were eventually retained.

Table 1. Sources of location information of *T. aureus* recorded from the literature. GBIF: Global Biodiversity Information Network (GBIF, https://www.gbif.org/; accessed on 16 June 2023).

Province	Location	Longitude (E)	Latitude (N)	Sources
Zhejiang	Wuyanling National Nature Reserve	119.673889	27.719722	[24]
	Fushan Township, Huangyan District, Taizhou city	120.887222	28.528056	[24]
	Jingning She Nationality Autonomous County	119.480833	27.878056	[25]
	Chimu Mountain of Jingning country	119.661667	27.924722	[26]
Fujian	Wuyi Mountain national nature reserve	117.753889	27.650278	[27]
	Dayun Mountain National Nature Reserve	118.175556	25.673333	[27]
	Meihua Mountatin National Nature Reserve	116.895795	25.294767	[27]
	Wuping County, Longyan City	116.695833	24.978056	[27]
	Liancheng County, Longyan City	116.878889	25.215833	[27]
	Qitai Mountain Provincial Nature Reserve	117.581944	26.948889	[27]
	Jian 'ou city Jiyang town, Nanping City	118.13741	27.13868	[27]
	Yongchun County, Quanzhou City	118.29424	25.32188	[27]
	Teng Mountain Provincial Nature Reserve	118.93258	25.86672	[28]
	Xiyang Village, Giring Town, Yongtai County	119.012778	25.772778	[28]

Table 1. *Cont.*

Province	Location	Longitude (E)	Latitude (N)	Sources
	Tianbaoyan National Nature Reserve	117.54574	25.93414	[28]
	Niumu Provincial Nature Reserve	117.468611	25.851389	[27]
	Xianyang town, Quanzhou City, Yongchun County	117.916111	25.409339	[27]
	Mandang Mountain National Nature Reserve	118.105833	26.680278	[29]
	Shuiji town, Jianyang district, Nanping city	118.179056	27.375248	GBIF
Jiangxi	Jinggang Mountain Provincial Nature Reserve	114.15	26.55	[15]
	Wuyi Mountain National Nature Reserve	117.716667	27.815278	[30]
	Jiulian Mountain National Nature Reserve	114.561389	24.608611	[30]
	Longnan County, Ganzhou City	115.429722	24.694444	[31]
	Taiyuan She township, Leadshan County, Shangrao city	117.483056	27.950278	[32]
	Tianzhu mountain township, Yanshan County, Shangrao city	117.731111	27.986389	[32]
	Pingshan Scenic spot	115.439722	25.704444	[25]
	Sanqingshan scenic spot	118.073056	28.905833	[25]
Hunan	Mang Mountain Provincial Nature Reserve	112.839722	24.909167	[33]
Guangdong	Nanling National Nature Reserve	113.04563	24.894098	[3]
	Northern mountainous area of Lianping County, Heyuan City	114.472778	24.501667	[3]
	Provincial Nature Reserve Management Office of South China Tiger Protection in Northern Guangdong	113.629722	24.896667	[33]
	Longnan City, Ganzhou City	114.625833	24.925278	[33]
Guangxi	Tiane town, Tiane County, Hechi City	107.12	24.87	GBIF
	Chengzhong district, Liuzhou City	109.422454	24.314681	GBIF
	Liuzhou Rongshui Miao autonomous county	109.264722	25.192222	[34]
	Rongan County, Liuzhou City	109.756667	25.486389	[33]
	Dayaoshan Nature reserve	110.315833	24.025556	[35]
	Dayaoshan Nature reserve	110.248056	24.168056	[35]
	Daming Mountain National Nature Reserve	108.402222	23.501944	[36]
Hainan	Wuzhi Mountion National Nature Reserve	109.543889	19.004444	[37]
	Shuiman township, Wuzhishan city	109.533313	18.785278	GBIF
	Jianfengling Nature Reserve	108.868611	18.724167	[33]

2.2. Acquisition and Selection of Bioclimate Variables

SSPs, as a new generation of socio-economic scenarios for climate change research, unify socio-economic assumptions used by various research communities, can serve as climate change projections, and facilitate integrated analyses of climate change impacts, vulnerability, adaptation, and mitigation. They also provide a basis for the assessment of climate policies and play an increasingly important role in predicting climate change and in related research and climate policy decisions [38,39].

In this study, future SSPs were used as climate data, and the new-generation climate system model BCC-CSM2-MR, developed by Beijing Climate Center (BCC) of China Meteorological Administration, was used as it can reasonably reproduce climate distribution characteristics. The correlation coefficient between the simulated results using this climate data and the observed values is 0.86, indicating that the model can well reproduce the climate distribution characteristics of China [40]. The SSP1_2.6 and SSP5_8.5 climate scenarios were used to predict the distribution of species under low radiative forcing and high radiative forcing. SSP1_2.6 assumes that the intensity of dependence on resources and fossil energy is artificially reduced, greenhouse gas emissions will be reduced to net zero around 2070, and the global average temperature increase will be 1.8 °C (1.3–2.4 °C) in 2081–2100 compared with that in 1850–1900. SSP5_8.5 emphasizes the traditional economic development orientation, with an energy system dominated by fossil fuels, resulting in substantial greenhouse gas emissions, and the global average temperature rise will be 4.4 °C (range: 3.3–5.7 °C) in 2081–2100 compared with that in 1850–1900 [3].

In order to improve the accuracy of prediction, this study combined the living habits of mountain butterflies and topographic data, and initially selected 19 bioclimatic variables (bio1–boi19) and elevation data (elev) with a spatial resolution of 2.5min. All the above environmental variables were obtained from WorldClim (http://www.worldclim.org; bioclimatic variables: accessed on 16 December 2023; https://www.worldclim.org/data/

cmip6/cmip6_clim2.5m.html, downloaded 16 December 2023; elevation variables: accessed on 16 December 2023; https://www.worldclim.org/data/worldclim21.html, downloaded 16 December 2023).

Using the Extract Multi-values to Point function of ArcGIS (version 10.8), data for environment variables at 42 occurrences were extracted. To avoid the effects of correlated variables on prediction results and improve estimates of the direct or indirect impacts of environmental parameters on target species [41], ENMtools was used to screen 20 environmental variables before modeling, and Spearman correlation coefficient coefficients were evaluated. When the correlation coefficient was greater than 0.8, one of the representative environmental factors was retained [42]. The filter environment variables were used for model construction (Table 2).

Table 2. Environmental variables retained after screening.

Variable	Description	Unit
bio4	Temperature seasonality	°C
bio6	Min. temperature of coldest month	°C
bio8	Mean temperature of wettest quarter	°C
bio12	Annual precipitation	mm
bio14	Precipitation of driest month	mm
bio18	Precipitation of warmest quarter	mm
bio19	Precipitation of coldest quarter	mm
elev	Elevation	m

2.3. Model Building and Testing

For high computational efficiency, the Biomod2 package was run with R4.2.4 in the study. Eleven models in the Biomod2 platform were used for modeling, including a generalized linear model (GLM), gradient boosted machine (GBM), classification and regression tree model (CTA), artificial neural network (ANN), surface distribution differentiation chamber model (SRE), flexible discriminant analysis (FDA), random forest (RF), maximum entropy model (MaxEnt), multivariate adaptive regression splines (MARS), extreme gradient boosting (XGBOOST), and generalized additive model (GAM). These algorithms have been applied for modelling environmental relationships for a wide range of species [43–49]. In addition to the MaxEnt model, the parameters optimized by the ENMeval package (regulated frequency multiplier RM = 0.5, feature combination LQ) were modeled, and the other models adopted the default settings recommended by Thuiller et al. [45]. To meet the modeling requirements of Biomod2 and better simulate the actual distribution, 1000 pseudo-missing data were randomly selected for modeling outside the suitable range predicted by the model [50]. To evaluate the performance of the species distribution model, the species distribution data were randomly divided into two parts: 75% as the training data set and 25% as the test data set [51]. To avoid the error caused by single modeling approaches, the above process was repeated 10 times for each model, resulting in 110 single total modeling results.

The area under the curve (AUC) and true skill statistics (TSS) were used to evaluate model performance; both parameters take values of [0,1]. The larger the value, the stronger the correlation between the distribution model and environmental variables, and the higher the accuracy of its prediction results [52,53]. When the AUC value ranges from 0.5 to 0.8, the prediction results of the model can be considered general. When the AUC value is greater than 0.8, the model has good or very good prediction performance [54]. TSS shares the advantages of Kappa in predicting species distributions in terms of the incidence, sensitivity, and specificity of occurrences but avoids the unimodal dependence on the incidence of distribution records [55]. When the TSS value is greater than 0.7, the prediction accuracy of the model is high [56]. After the model prediction results were derived for the single models, the five models with the highest TSS and AUC values were selected to construct a combined model.

2.4. Data Processing

After the selected environmental and distribution data for *T. aureus* were input into the combined model, the data generated from the model were visualized using ArcGIS 10.8. Jenks method for grading was used to divide the threshold of suitable area of *T. aureus*. According to Zhang's study [28], the threshold was set and *T. aureus* was divided into four levels: non-suitable areas (0–0.1), low suitability areas (0.1–0.3), medium suitability areas (0.3–0.6), and high suitability areas (0.6–1). The area of the reclassified layer was tabulated by grid calculation, and the weight of each partition was obtained. Then, the area of each level was converted according to the actual area of the land cut out. The SDMtoolbox (version 2.5) toolkit was used to calculate the centroid position and migration direction of the habitat area of *T. aureus* in three periods under different climate scenarios.

3. Results

3.1. Evaluation of Model Prediction Accuracy

Based on AUC and TSS values, the prediction accuracies of single models and the combined model were evaluated (Table 3). The SRE had the worst prediction accuracy, with AUC and TSS values of 0.735 and 0.470, respectively, which could not simulate the distribution of suitable areas correctly. Except for the model constructed using the SRE algorithm, AUC values of all models were greater than 0.8 and TSS values were greater than 0.7, indicating that the models constructed based on a single algorithm could effectively predict the suitable areas of *T. aureus*. In particular, ANN, MARS, GLM, RF, and CTA yielded good simulation results for the suitable areas of *T. aureus*. Therefore, these five models were selected to build a combined model, and the prediction accuracy of the model was evaluated again. AUC and TSS values of the combined model were 0.990 and 0.972, respectively, both of which were greater than those of each of the single models and the prediction accuracy was higher, indicating that the prediction results of the suitable areas of *T. aureus* were excellent.

Table 3. AUC and TSS values of ensemble model and single models.

Item	Algorithm											
	ANN	**CTA**	**FDA**	**GAM**	**GBM**	**GLM**	**XGBOOST**	**MARS**	**MAXENT**	**RF**	**SRE**	**ESM**
AUC	0.981	0.902	0.862	0.862	0.983	0.975	0.922	0.977	0.968	0.963	0.735	0.990
TSS	0.845	0.805	0.805	0.725	0.855	0.905	0.740	0.835	0.750	0.815	0.470	0.972

3.2. Importance Assessment of Bioclimatic Variables

An analysis of the importance of bioclimatic variables (Figure 2) revealed that annual precipitation (bio12), the precipitation of the driest month (bio14), and the minimum temperature of the coldest month (bio6) had the greatest impact on the habitat area of *T. aureus*. In addition, there was seasonal variation in temperature (bio4), elevation (elev), warmest quarterly precipitation (bio18), wettest quarterly average temperature (bio8), and coldest quarterly precipitation (bio19). In general, temperature, precipitation, and altitude had important effects on the habitat range of *T. aureus*.

According to the response curves of major environmental factors (Figure 3), the habitat suitability of *T. aureus* species increases significantly when the annual precipitation reaches about 1700 mm and the lowest temperature in the coldest month reaches about 3 degrees. The habitat suitability of *T. aureus* species first increases and then decreases in the driest month precipitation, indicating that it is more suitable for *T. aureus* to distribute in warm and humid areas with abundant rainfall.

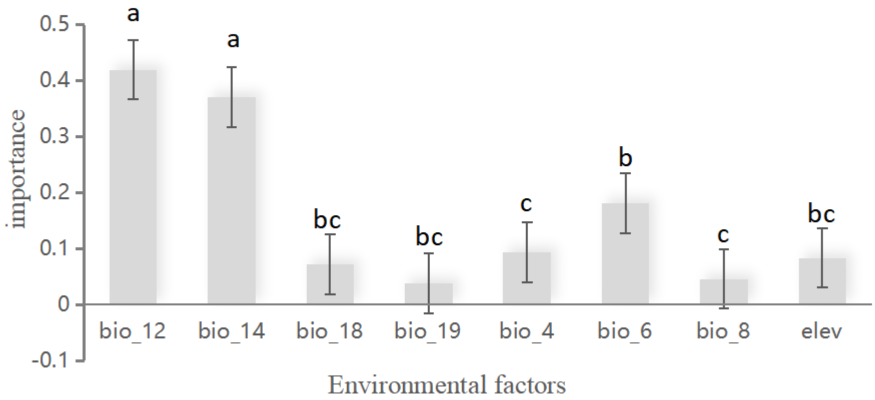

Figure 2. Relative contributions of environmental variables to the species distribution model for *T. aureus*. Different letters in the table indicate a statistically significant difference (meantstandard deviation, meantSD) (Kruskal–Wallis $p < 0.05$).

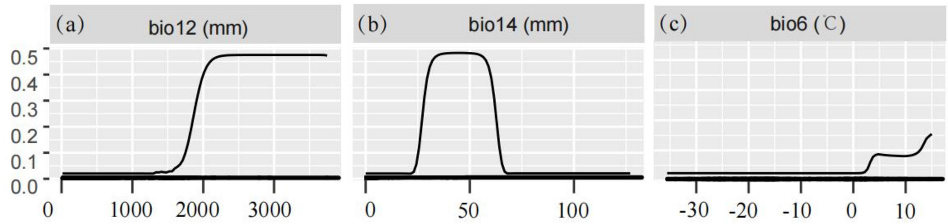

Figure 3. Response curves for the main environment variables, (**a**) suggests bio12 (unit: mm); (**b**) suggests bio14 (unit: mm); (**c**) suggests bio6 (unit: °C).

3.3. Prediction of the Suitable Zone of *T. aureus*

As determined from the combined model (Figure 4), the current habitat area was mainly located in southern China, and the habitat range was 92° E–122° E, 31° N–18° N. At present, the total habitat area of *T. aureus* was 138.95 × 10^4 km^2, of which the highly suitable habitat area was 344,300 km^2, mainly concentrated in Fujian, northern Guangdong, northeastern Guangxi, southern Jiangxi, southern Zhejiang, southern Hainan, and other areas. The moderately suitable area covered 41.47 × 10^4 km^2, mainly located in northern Hainan, northern Taiwan, and Guangxi, and scattered in southern Yunnan, Guangdong, Guizhou, Hunan, Zhejiang, Jiangxi, and other places. The low suitability area covered 63.05 × 10^4 km^2, mainly located in central Zhejiang, western Hunan, southern Chongqing, southern Guizhou, southern Yunnan, southwest Guangxi, and southwest Taiwan, and scattered in Sichuan, Anhui, Hubei, Xizang, and other places. Comparing the actual records of *T. aureus* with the map of habitat suitability based on the combination model, *T. aureus* had a large area of suitable habitat outside of known occurrences, including high suitability values in some areas of Taiwan (i.e., >0.3).

The combined model was used to simulate the future suitable habitat of *T. aureus* under the influence of climate change (Table 4, Figures 5–7). Comparing the predicted suitable habitat areas in different periods revealed different responses of *T. aureus* to climate change. The habitat range in the three periods in China was predicted to decrease to a large extent. The two climate emission scenarios revealed that *T. aureus* will shrink in the Yunnan, Guizhou Guangdong, Guangxi, and other provinces, in addition to its original distribution (Figure 8). *T. aureus* was the most sensitive to climate change under SSP5_8.5. Compared with the current climate conditions, when 2050s (SSP1_2.6) was adopted, the suitable area of *T. aureus* decreased by 32.43 × 10^4 km^2, which is 23.34% less than the current suitable area. When the scenario SSP1_2.6(2070s) was adopted, the suitable area of *T. aureus* decreased by 54.42 × 10^4 km^2, which is 39.17% less than the current suitable area. When the scenario SSP1_2.6 (2090s) was adopted, the suitable area of *T. aureus* decreased by 62.02 × 10^4 km^2, which is 44.63% less than the current suitable area. When the scenario SSP5_8.5

(2050s) was adopted, the suitable habitat area of *T. aureus* decreased by 53.27 × 10^4 km^2, which is 37.75% less than the current suitable area. When the scenario SSP5_8.5 (2070s) was adopted, the suitable habitat area of *T. aureus* decreased by 57.88 × 10^4 km^2, which is 41.20% less than the current suitable area. When the scenario SSP5_8.5 (2090s) was adopted, the suitable habitat area of *T. aureus* decreased by and 77.92 × 10^4 km^2, which is 56.07% less than the current suitable area. In the 2070s, compared with the 2050s, the area of high suitability area increased by 3.72 × 10^4 km^2 and 3.04 × 10^4 km^2, respectively, under SSP1_2.6 and SSP5_8.5; however, the total suitable area still decreased. By the 2090s, under the two climate scenarios, the area of suitable habitat decreased by 44.6% and 56.1%, respectively, compared with the current suitable habitat, and Sichuan and Tibet were no longer suitable under the two climate scenarios.

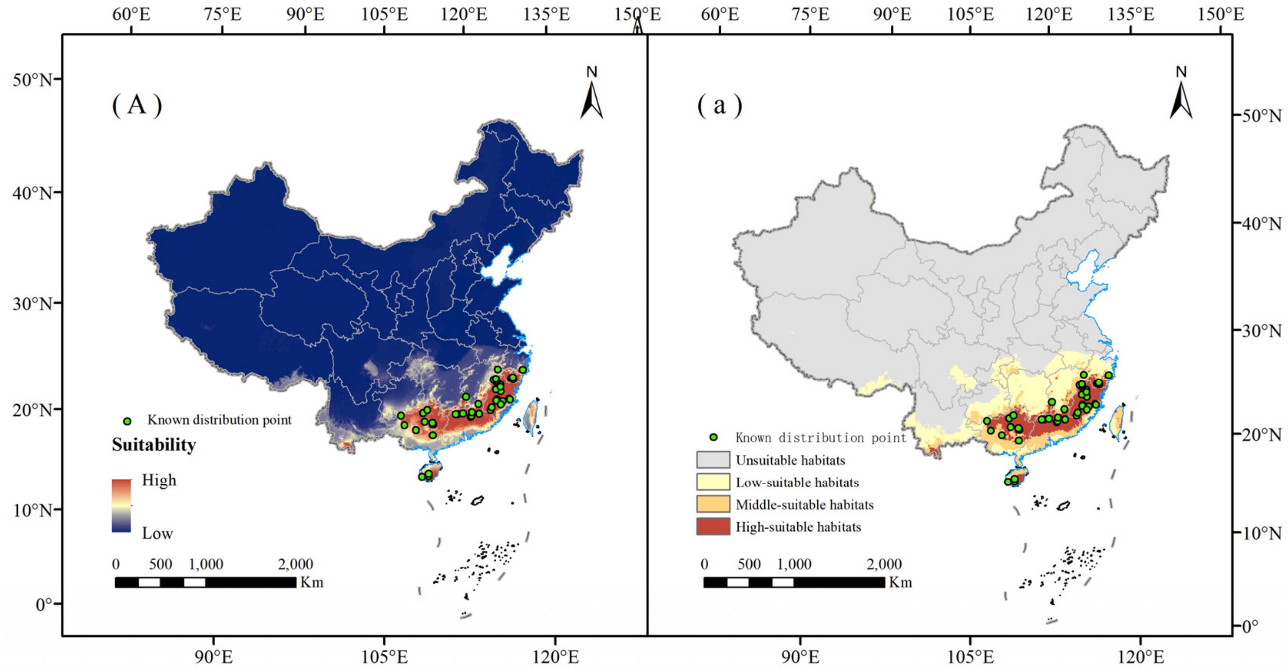

Figure 4. Current suitable habitat distribution of *T. aureus* in China. Red suggests increase in habitat suitability while blue suggests decrease in habitat suitability (**A**). Gray suggests unsuitable habitats, yellow suggests low-suitable habitats, orange suggests middle-suitable habitats, and red suggests high-suitable habitats (**a**).

Table 4. Ensemble Model predicted potential suitable habitats areas of *T. aureus* under different scenarios/10^4 km^2.

	High-Suitable Habitats	**Middle-Suitable Habitats**	**Low-Suitable Habitats**	**Total-Suitable Habitats**
current (1970–2000)	34.43	41.47	63.05	138.95
2050s SSP1_2.6	15.82	38.64	52.06	106.52
2070s SSP1_2.6	19.54	26.11	38.88	84.53
2090s SSP1_2.6	16.83	25.60	34.49	76.93
2050s SSP5_8.5	19.02	34.60	32.88	86.50
2070s SSP5_8.5	21.24	34.50	25.96	81.70
2090s SSP5_8.5	12.17	21.20	27.66	61.04

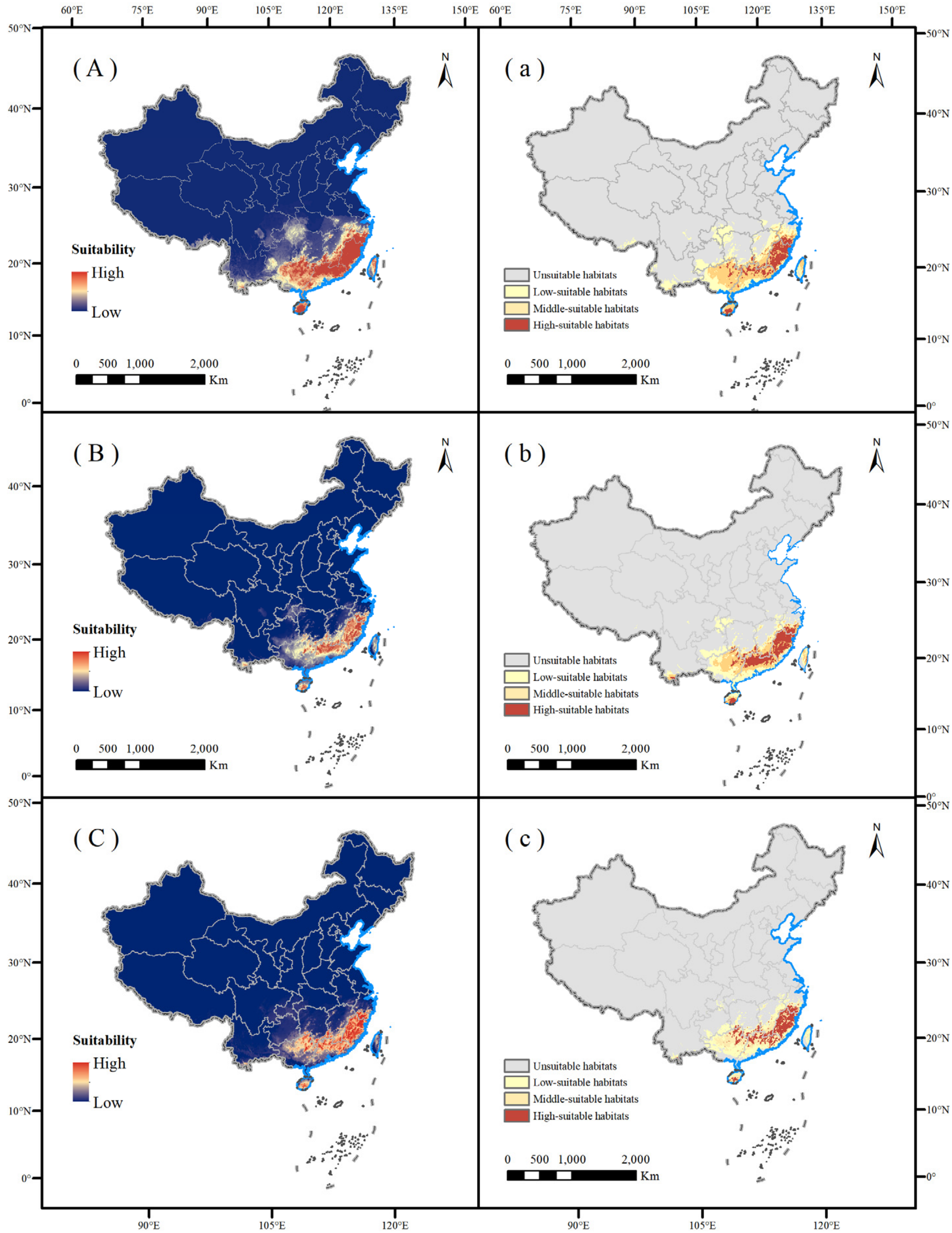

Figure 5. Suitability and distribution change of *T. aureus* in the scenarios SSP1_2.6. (**A**) Suitability in the 2050s; (**a**) Suitable habitat in the 2050s; (**B**) Suitability in the 2070s; (**b**) Suitable habitat in the 2050s; (**C**) Suitability in the 2090s; (**c**) Suitable habitat in the 2090s. Red suggests an increase in habitat suitability while blue suggests a decrease in habitat suitability (**A**,**B**,**C**). Gray suggests unsuitable habitats, yellow suggests low-suitable habitats, orange suggests middle-suitable habitats, and red suggests high-suitable habitats (**a**,**b**,**c**).

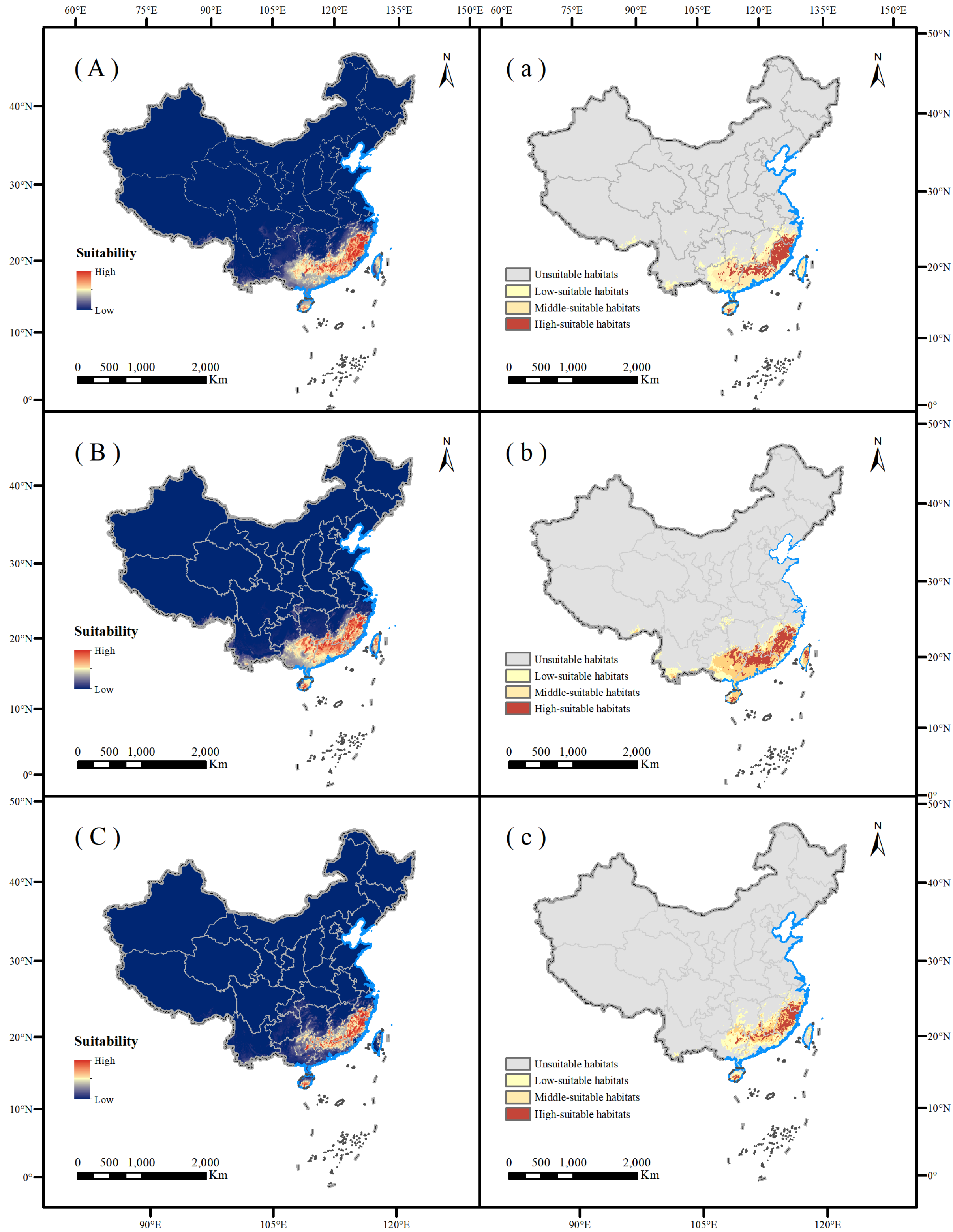

Figure 6. Suitability and distribution change of *T. aureus* in the scenarios SSP5_8.5. (**A**) Suitability in the 2050s; (**a**) Suitable habitat in the 2050s; (**B**) Suitability in the 2070s; (**b**) Suitable habitat in the 2050s; (**C**) Suitability in the 2090s; (**c**) Suitable habitat in the 2090s. Red suggests an increase in habitat suitability while blue suggests a decrease in habitat suitability (**A**,**B**,**C**). Gray suggests Unsuitable habitats, yellow suggests low-suitable habitats, orange suggests middle-suitable habitats, and red suggests high-suitable habitats (**a**,**b**,**c**).

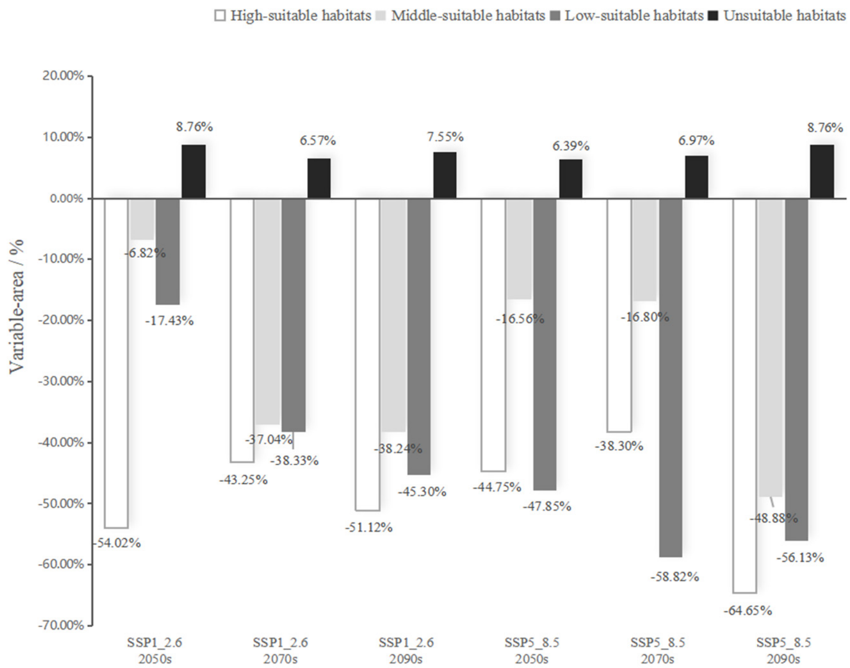

Figure 7. Change in the area of the suitable habitats of *T. aureus* in future climate scenarios in China. White suggests the area change of high-suitable habitats, light gray suggests the area change of low-suitable habitats, dark gray suggests the area change of middle-suitable area, and black suggests the area change of unsuitable habitats.

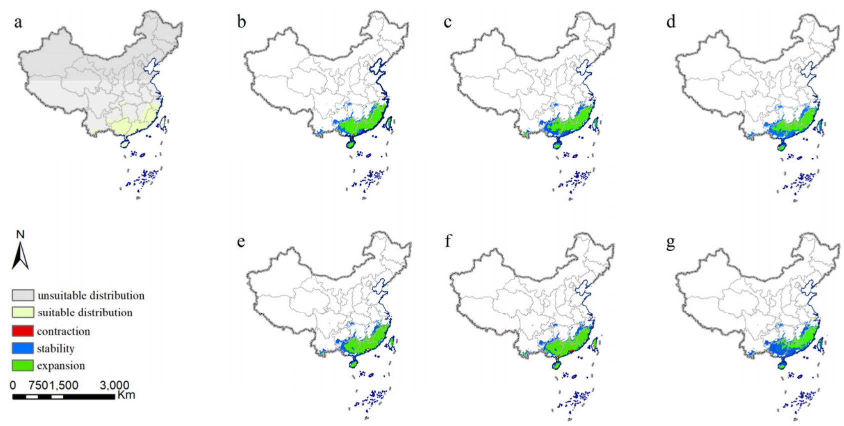

Figure 8. Potential distribution of *T. aureus*. Potential distribution in the current climate is depicted in the map below, with yellow indicating a suitable habitat for growth (**a**). Extrapolating from the current climate to the future (2050s), the scenarios SSP1_2.6 (**b**); 2070s, SSP1_2.6 (**c**); 2090s, SSP1_2.6 (**d**); 2050s, SSP5_8.5 (**e**); 2070s, SSP5_8.5 (**f**); 2090s, SSP5_8.5 (**g**) were considered. Blue indicates areas in the potential distribution that will disappear in the future. Green indicates areas where the potential distribution will not change in the future. Red indicates new potential distribution areas.

3.4. Migration Route of the Centroid in Future Suitable Areas

In terms of spatial patterns, there were differences in the migration of *T. aureus* under different climate scenarios (Figure 9). At present, the population centroid of *T. aureus* was located in Xinning County, Shaoyang City, Hunan Province (111.26° E, 26.53° N). Under SSP1_2.6 in the 2050s and 2070s, the centroid of the suitable area of *T. aureus* migrated to the south. In the 2050s, the centroid of the suitable area of *T. aureus* was located in Changning City, Hengyang City, Hunan Province (112.58° E, 26.30° N), travel distance 133.58 km.

The 2070s, the centroid was located in Guiyang County, Chenzhou City, Hunan Province (112.62° E, 25.87° N), travel distance 47.24 km again. In the 2090s, the center of mass shifted northward and was located in Yongxing County, Chenzhou City, Hunan Province (112.79° E, 26.17° N), having moved 32.26km to the northeast from 2070s. When the climate scenario was set to SSP5_8.5, the center of mass migrated southeast to Guiyang County, Chenzhou City, Hunan Province (112.53° E, 26.06° N) in the 2050s, travel distance 133.58 km; and southwest to Shuangpui County, Yongzhou City, Hunan Province (111.51° E, 25.88° N) in the 2070s, travel distance 104.72 km. By the 2090s, the centroid of *T. aureus* moved northwest to Chaling County, Zhuzhou City, Hunan Province (113.79° E, 26.73° N). It moved 246.4 km to the northeast from 2070s. Under the future climate change scenarios, global warming and increasing humidity will have migrated to the south slightly, on the centroid of the suitable habitat area of *T. aureus* in China; however, with the further change of climate, the centroid of *T. aureus* shifted to the northeast.

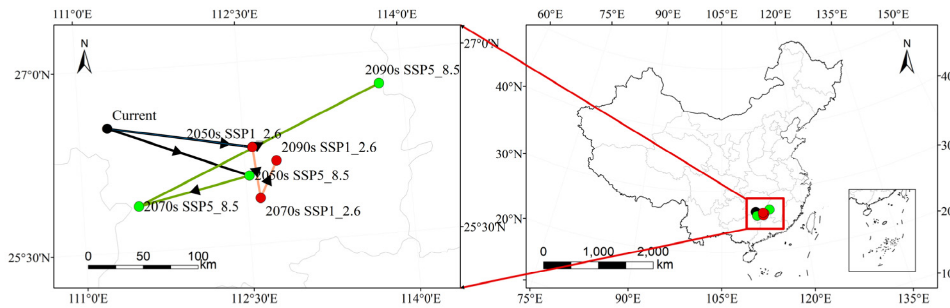

Figure 9. Change in centroid of the suitable region of *T. aureus* in future climate scenarios. The black point suggests the position of the center of mass, the green point suggests the position of the center of mass in the SSP5_8.5 climate scenario, the red point suggests the position of the center of mass in the SSP1_2.6 climate scenario, and the arrow represents the direction of movement of the center of mass.

4. Discussion

4.1. Reliability of Habitat Suitability Prediction Results

In the process of simulating the appropriate distribution of *T. aureus* and future changes in resources using the Biomod2 package, the accuracies of the ANN, MARS, GLM, RF, and CTA models were high, and the accuracy of the integrated model was higher than those of the single models. It indicates that the ensemble model can better predict the distribution and change of *T. aureus* than the single model. The prediction results showed that the habitat area of *T. aureus* is mainly distributed in Fujian, Guangxi, Guangdong, Hainan, and other tropical and subtropical areas in China. It is basically consistent with the known distribution results at present. Compared with the prediction results obtained by Zhang [28], the predictions in this study showed a wider range in southern Yunnan and southern Tibet. Compared with the prediction results of Xing et al. and Wang, the results of this study showed a wider range in China. In addition to the slight differences in distribution records (this study included more distribution records in China), differences in the selection of environmental variables, variable screening methods, and parameter settings can explain the deviations in the final prediction results. It is very important to select the least correlated and biologically reasonable predictors to improve model accuracy [39].

4.2. Effects of Future Climate Scenarios on the Distribution of T. aureus

The distribution of *T. aureus* is restricted by various environmental conditions. In the screening of environmental variables, temperature and precipitation determined the potential geographical distribution of *T. aureus* to a certain extent. Bio12, bio14, and bio6 are the main environmental factors affecting the distribution of *T. aureus*. This is consistent with the actual survey results [16]. Hydrothermal conditions play a major role in the potential distribution of *T. aureus* in addition to topographic factors [56]. Overall, changes in temperature and precipitation may be the primary explanations for the loss of suitable northern areas.

The migration path of the centroid of suitable area for *T. aureus* differed among scenarios. The directions of migration were south and north, respectively, under SSP1_2.6 and SSP5_8.5. Many butterfly species tend to expand northward or to higher elevations due to environmental changes or retreat to areas with favorable terrain and microclimate conditions [57]. However, mountain species usually occupy specific climatic niches and are highly sensitive to environmental changes. For example, Habel et al.'s study [58] on *Lycaena helle*, Rodder et al.'s study [57] on the distribution of butterflies in alpine mountains, Filazzola et al. [59]'s study on the host plants of mountain butterflies, and Grabherr et al.'s study [60] on alpine flora and vegetation all proved this point; these species can generally only migrate to higher altitudes in the context of climate change [58]. In this study, in the 2050s and 2070s, the centroid moved southward under the two climate scenarios, which may indicate a shift to high altitudes, and the northern suitable area was lost first. After the 2090s, the centroid shifted to the north under both climate scenarios, and the southern suitable area was gradually lost.

There are no records of capture of *T. aureus* in Taiwan, Tibet, and other suitable areas in the prediction results. This may be due to the biological characteristics (for example, the migration ability is poor, the parasitic plant is single, and the flying ability is weak [61]) of *T. aureus* and its specific habitat requirements, which limits the distribution of the species. Once the original habitat is lost, it is difficult for the species to spread to other suitable habitats, creating an extinction risk. In addition, in the predicted range of suitable areas, due to the influence of human activities, the original forests in the current habitat of *T. aureus* have been largely reduced, most of which are young forests, and the stand structure has changed [62]. This decreased the available habitat of *T. aureus* and may be one of the reasons for the discrepancy between the butterfly's habitat area and its distribution area. This limits gene exchange, thereby reducing genetic diversity and environmental adaptability and increasing the extinction risk [63].

According to the prediction results obtained using Biomod2, the habitat area of *T. aureus* showed a trend of first drastic reduction and then slight reduction with the warming and humidification of the climate. In particular, in the SSP5_8.5 scenario, climate change was predicted to have a serious negative impact on the distribution of *T. aureus*. In the 2090s, the overall habitat area of highly suitable area decreased by 51.12% and 64.65%, respectively, compared with the current situation. The biomod2 platform is used to evaluate the species niche and project it into the landscape, which can intuitively present the species occurrence probability, habitat suitability, or species richness, etc., and provide important decision-making basis for wildlife protection, nature reserve optimization, and nature reserve system construction in China.

In this study, we screened bioclimatic variables according to their correlation, ensuring maximum retention of species biological information while avoiding collinearity and redundant information. In order to understand the specific environmental requirements of *T. aureus*, this study established a combination model with small samples and more accurate biomod2 package, which has been widely used in *Paeonia lactiflora*, *Populus davidiana*, and other species. Understanding the habitat distribution of *T. aureus* and the impact of future climate change on its potential geographic distribution will be of great significance to the development of conservation planning and the enhancement of species protection. However, this study has some limitations because it does not use continuous climate change parameters and only climate and elevation were considered, and host plants, biological factors, and human interference were not superimposed. Therefore, multiple environmental factors, such as host plants, will be introduced in future studies to further improve the prediction accuracy; the response interval and its numerical range of climate change are needed in the future. In summary, a combined model was used to predict the potential distribution under the current and future climate scenarios in China, clearly revealing that climate change would lead to a significant reduction in the suitable habitat of this insect, which may lead to an extinction risk.

5. Conclusions

In this study, we evaluated the distribution of *T. aureus* in China. We also predicted the main potential distribution areas of *T. aureus* under current and future climate conditions. Through modeling and prediction, the potential distribution of *T. aureus* under the current climate in China is mainly concentrated in south China. With the changing climate, the suitable area for *T. aureus* will gradually move southward, then move northeast. The potential distribution of the natural enemies of *T. aureus* will reduce under climate change. The prediction results revealed that future climate change will decrease the potential distribution of *T. aureus*. This prediction has high reliability, accurately predicts the suitable range and degree of *T. aureus*, and has important significance for the protection of *T. aureus* in the future. At the same time, we should also vigorously promote energy conservation and emission reduction, strengthen habitat protection and restoration, carry out research on artificial breeding technology, strengthen public protection publicity, and jointly help *T. aureus* out of the threat of extinction.

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