Habitat protection and planning for Leonurus japonicus using the Maxent and Marxan models

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Abstract

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Abstract

To predict suitable growing regions for *Leonurus japonicus* and to provide scientific sopport for the habitat conservation and the exploitation and utilization of germplasm resources under climate change conditions, this study combined niche and priority conservation models to assess the future potential distribution of *L. japonicus* in China. To this end, distribution points and samples of *L. japonicus* were gathered through online and field surveys. The Maxent model with optimized parameters was used for predicting the suitable habitats of *L. japonicus* at different stages, and the Marxan model was used to determine the priority of protected areas. The results showed that the highest temperature in the hottest month, the lowest temperature in the coldest month, the precipitation in the wettest month, the precipitation in the driest month, and altitude were the main environmental factors influencing the distribution of *L. japonicus* . Under the three climate change scenarios, the centroid of the suitable area of *L. japonicus* migrated northward, and the migration position tended to expand further northwest. In the future, there would be no significant niche differentiation of *L. japonicus* ; the Marxan results showed that priority protected areas for*L. japonicus* were in southwestern central China, Lingnan, southern east China, and Guizhou. Overall, the results of this

research can provide a strategy for the determination of priority protection areas for *Leonurus japonicus* in China.

Keywords: *Leonurus japonicus* ; Maxent model; ENMeval packet; Marxan model; suitable area prediction

1. Introduction

In the sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC), it was pointed out that the impact and risk of climate warming are becoming increasingly complex, and this has produced a series of irreversible effects on ecosystems and human societies. Global warming will outweigh habitat destruction as the greatest threat to biodiversity in the coming decades (Li et al., 2021). In terms of species distributions, climate change will have a driving effect on the distributions of plants, so that the suitable area of migration (Li et al., 2021) and the changes in species distribution ranges will have a certain risk to human beings. Therefore, to help human society cope with changes in the distribution of species in response to climate change, suitable habitat distribution prediction is particularly important, and current research reports show that the predictions of climate change scenarios concerning species' suitable area have become a focus in plant protection research, especially in the study of medicinal plants (Zhang et al., 2019; Zhang et al., 2020; Gupta et al., 2021).

There are many habitat suitability models, including mechanism models, regression models, machine learning models, and niche models; however, the niche model has become the main application model used to study the suitability distributions of species. Among these, the Maxent model has the highest feasibility and prediction accuracy (Li et al., 2021) and thus is considered to be the most effective prediction method (Zhan et al., 2022). This model can not only integrate multiple environmental variables when predicting potential distributions but also obtain the main influencing factors and adaptation range that affect the growth of the species. It has been widely used to predict the possible distribution of species and to study ecological characteristics (Zeng et al., 2021).

Leonurus japonicus is an annual or biennial herb of the family Labiatae. It is distributed throughout China and grows in a variety of habitats, especially in areas with the sun exposure, at altitudes of up to 3400 meters. *Leonurus japonicus* prefers a warm and humid climate, and the plants can grow in most soils. *Leonurus japonicus* is a traditional Chinese herbal medicine. Its fresh or dry aboveground parts can be used as a medicine. It has the effects of regulating menstruation, diuresis, and swelling; removing blood stasis; promoting blood circulation and hemostasis; and preventing miscarriage (Wang et al., 2022; Zhang et al., 2000). It was used as a gynecological drug in traditional Chinese medicine during past dynasties. It is also widely used in the production of gynecological Chinese patent medicines today, and the market demand is high (Jiang, H., 2009). Environmental conditions such as light, temperature, and water affect the growth and accumulation of total alkaloids in plants.

At present, the research on *Leonurus japonicus* primarily focuses on its pharmacological aspects and chemical composition, while the prediction of potential distribution areas under future climate change scenarios has not been considered. Maxent has been used to predict suitable areas of endangered species, biological invasive species, crops, and medicinal plants (Zeng et al., 2021; Li et al., 2021). To clarify the distribution of the suitable area of the medicinal plant*Leonurus japonicus* and its response to future climate change, this study employed the ENMeval package to optimize the parameter settings in the Maxent model (Muscarella et al., 2015), and the optimized model was used to predict and analyze the suitable distribution of *L. japonicus* . On this basis, according to the potentially suitable area under the current climatic conditions, the Marxan model was used to derive the priority protection area of*Leonurus japonicus* . The appropriate ecological environment for planting can be determined to avoid the loss caused by blind introduction. The results can provide a reference for the rational conservation of Chinese herbal medicines.

2. Research methods

2.1. Collection of species geographical distribution data

Through the retrieval from plant herbaria such as the Chinese Virtual Herbarium (CVH) and the Global

Biodiversity Information Facility (GBIF), any repeated or incorrect distribution point data were eliminated. For the distribution points with detailed information, the longitude and latitude were conformed by the Baidu coordinate system, and a total of 489 distribution data points of *Leonurus japonicus* specimens were collected (Figure 1).

2.2. Selection and processing of environmental variables

Species niches are affected by climate, topography, biology, and other factors. After considering the comprehensiveness and complexity of ecological factors, 34 environmental variables that could reflect species niches were selected. The list included 19 bioclimatic factors, 14 soil factors, and one topographic factor (altitude).

The current (1970–2000), 2050s (2041–2060), and 2090s (2081–2100) bioclimatic factor data used in this research were derived from the world climate database Worldclim (http://www.worldclim.Org), and the spatial sampling rate of the data was 2.5 arc-minutes (~5 km). The climate data of the 2050s and 2090s were obtained from the Beijing Climate Center-Climate System Model-Medium Resolution (BCC-CSM2-MR), one of the Coupled Model Inter-Comparison Project Phase 6 (CMIP6) datasets, which included three scenarios: sustainable development (ssp126), intermediate development (ssp245), and conventional development (ssp585). Ssp data have a high accuracy and separation rate and can integrate local development factors, and so are more convincing than CMIP5 data. The data of soil factors and topographic factors were from the World Soil Database (HWSD) of the FAO (http://www.fao.org/faostat/en/#data), and the map data were from China's Ministry of Natural Resources (http://www.mnr.gov.cn/).

In the application of species distribution models, the accuracy of the Maxent model can be improved by using the R language, variance inflation factor (VIF)-based environmental variable screening, and Spearman correlation to reduce the multicollinearity between multiple environmental variables. In this study, the R language package was used to preliminarily screen the factors with correlations less than 0.7, and then on this basis, the factors with variance inflation factor VIF less than 5 were selected. The R language was used for Pearson correlations, and factors with correlation coefficients less than 0.7 were retained. At the same time, factors with extremely high ecological significance were retained among the factors with correlation coefficients greater than 0.7 (Zhang et al., 2017). Finally, six climatic factors, one topographic factor, and five soil factors were selected, for a total of 12 environmental factors (Table 1).

Table 1 The environmental aspects used in the modeling

Type	Variable code	Environmental factor	Unit
Climatic factor	bio4	Variation coefficient of air temperature	1
	bio5	The highest temperature in the hottest month	×10°C
	bio6	The lowest temperature in the coldest month	×10°C
	bio7	Annual range of temperature	×10°C
	bio13	Precipitation of the wettest month	mm
	bio14	The driest monthly precipitation	mm
Topographic factors	elev	Altitude	m
Soil factor	t_cec_soil	Cation exchange capacity of topsoil	%
	t_ece	Electrical conductivity of topsoil	dS/m
	t_gravel	Gravel volume in topsoil	%
	t_oc	Organic carbon content in topsoil	%
	t_silt	Silt content in topsoil	%

2.3. Construction of the species distribution model

In this research, the Maxent model was used to predict the species suitability distribution of *L. japonicus* in three periods. A total of 489 distribution sample data points and 12 environmental factors were imported into Maxent 3.4.4 software for modeling. We used 75% of the distribution samples randomly chosen as training data for modeling, and 25% of the distribution samples were used as test data to evaluate the model's ability. Bootstrap replicates were set to 10, and the distribution value was output in the logistic form. The weight of each environmental factor was evaluated by the knife-cut analysis method, and the dominant environmental factor was determined by combining the percentage contribution of each environmental factor and the replacement importance value.

The knife-cut analysis method represents the importance of the explanatory variables based on the arrangement, reveals the importance of the variables, and is a highly reliable way for assessing a model. The accuracy value of the AUC-ROC of the test data represents the model fitting degree and indicates the prediction reliability of the model (Khan et al., 2022). The evaluation result of the AUC is a value in the range of 0.5–1.0; the greater the AUC value, the more precise the prediction. A result in the range 0.5–0.6 indicates that the simulation result is unqualified; 0.6–0.7 indicates poor simulation results; 0.7–0.8 indicates the general simulation results; 0.8–0.9 indicates that the simulation results are good; 0.9–1.0 indicates the good prediction effect (Ouyang et al., 2019; Wang et al., 2018; Wang et al., 2021).

2.4 Optimization of the model

Referring to Robert Muscarella's latest optimization method, the Checkerboard2 method was used to divide the study area into four bins. This masked geographic structure method can better adjust the model regularization level. The Maxent model regularization level consists of two parameters, the regularization multiplication value (RM) and the feature combination (FC) optimized by calling the ENMeval packet in the R language. The Maxent model provides five features: a linear feature (L), a quadratic feature (Q), a fragmented feature (H), a multiplicative feature (P), and a threshold feature (T). In this research, the default parameters of Maxent software were RM = 1.5 and FC = H; to optimize the Maxent model, the RM was set to 0.5–4; and each increase was by 0.5. There were a total of eight control frequency doublings, and six combinations with one or more features were used: L; L and Q; H; L, Q and H; L, Q, H and P; and L, Q, H, P and T. According to the permutations and combinations, 48 parameter combinations were calculated. The ENMeval data package uses the above 48 combinations of parameters to test the complexity of the model based on the delta AICc value and a 10% test miss rate, where the lower the value, the more accurate the model prediction (Phillips et al., 2017; Zhao et al., 2021).

2.5. Data processing

ArcGis10.4.1 software was used to divide and visualize the suitability of *Leonurus japonicus* . The suitability threshold of*Leonurus japonicus* was predicted based on the Maxent model. The natural breakpoint method was used to derive the habitat suitability index of *L. japonicus* . The minimum level of threshold establishment was 0.47, and the distribution below this level was excluded. Therefore, the habitat suitability grade of *L. japonicus* was divided into unsuitable area (0–0.47), low suitable area (0.47–0.55), moderate suitable area (0.55–0.65), and most suitable area (0.65–1). We compared the differences in the suitable areas of*Leonurus japonicus* in different periods to obtain the change map of the spatial distribution pattern of *Leonurus japonicus* under future climate change scenarios. The SDMTool data package in the R language was used to calculate the centroid position of the suitable area of *L. japonicus* under six different economic paths in the current and future periods, and the migration direction of the spatial distribution of the suitable area of *L. japonicus* was reflected by the change in the centroid position. The geosphere data package in the R language was used to calculate the centroid migration distance of*Leonurus japonicus* under different economic scenarios. The ArcGis overlay tool was used to overlay the current and future suitable area distribution data layers. The tool can merge different raster data into one output to define the specified set, reclassify the new layer, and divide the suitable level to obtain the final suitable zoning map of*Leonurus japonicus* . In this study, three suitable grades of low suitable area, medium suitable area, and highly suitable area were taken as the total suitable area; the values of dominant environmental variables and the suitability of different periods were extracted from 489 distribution points to analyze the relationship between environmental factors and potential distribution areas.

2.6. Niche differentiation analysis and priority reserve analysis

This study quantitatively analyzed niche differentiation in current and future periods. Based on the natural distribution points and environmental factor layers of the current period, the ecospat package for the R language was used to analyze and visualize niche differentiation, and the niche parameter D that ranges from 0 to 1 was calculated, indicating niches that are non-overlapping to fully overlapping (Warren et al., 2008; Yan et al., 2021). The software ENMTools v1.4 was used to calculate the niche breadth in the geographical and environmental space of each period as the average Levins B1 (inverse concentration) and B2 (uncertainty) values of the habitat suitability map for each period (Warren et al., 2008; Levins et al., 1968). Levins B1 and B2 values range from 0 to 1, with values close to 0 representing a narrow niche breadth and values close to 1 representing a wide niche breadth (Yuan et al., 2021).

The priority reserve is a protected area with a relatively large designated suitability index value. The main feature of this area is that the number of national key protected plant species is relatively large and less disturbed by human activities. Marxan shows wonderful performance in identifying priority protected areas, and it has been applied to system protection planning (Da Luz Fernandes et al., 2018; Carrasco et al., 2020; He et al., 2021). Based on the analysis results of the Maxent model, the main environmental factors selected were used for Marxan modeling. According to the distribution of the target species, the locations of the protected areas were determined to achieve the purpose of biodiversity conservation (Zhang et al., 2021).

3. Results and analysis

3.1. Model optimization and accuracy evaluation

Based on 489 distribution points, 12 layers of environmental variables, and the AIC information criterion, the Maxent model was used to simulate and predict the potential distribution area of *L. japonicus* . Under the default parameter settings of Maxent, the magnification RM = 1, the feature combination FC = LQHPT, and delta AICc = 6.99. When RM = 1.5, FC = H, and delta AICc = 0, the model was optimal, and the 10% training omission rate was 13.48% lower than that of the model under the default parameters (Table 2).

Therefore, the control frequency doubling RM = 1.5 and the feature combination FC = H were selected as the final parameters of the model. The AUC value of the simulation training under these parameters was 0.830. The standard deviation was 0.006 (Figure 2), indicating that the prediction results were accurate.

Table 2 Evaluation results of the Maxent model under different parameter settings

Model evaluation	Feature combination	Regularization multiplier	Value of delta Akaike information criterion corrected	10% Training omission rate
Default	LQHPT	1	6.99	0.29873
Optimized	H	1.5	0	0.25847

3.2. Potential geographical distribution of *Leonurus japonicus* in China

The Maxent model was used to simulate the distribution map of the suitable area of *L. japonicus* in the current period (Figure 3). The area highly suitable for *L. japonicus* in the current period was 135,620 km^2; the moderately suitable area was 1,043,933 km^2; and the low suitable area was 1,202,780 km^2. These areas were distributed in 27 provinces and cities: Shanxi, Shaanxi, Shandong, Henan, Jiangsu, Zhejiang, Anhui, Hubei, Chongqing, Sichuan, Yunnan, Guizhou, Jiangxi, Fujian, Guangxi, Guangdong, and other places. Highly suitable areas were concentrated in southwestern Hubei, western Guangxi, southeastern and northwestern Zhejiang, northeastern Guangdong, southern Fujian, eastern Hunan, and southwestern Jiangxi.

3.3. Prediction of suitable growing areas for *Leonurus japonicus*under future climate scenarios

Under the future climate scenarios, the predicted total suitable area of*L. japonicus* in the 2050s and 2090s would be reduced by varying degrees compared with the current period (Table 3). In the 2050s, compared with the current period, the total suitable area of *L. japonicus* decreased under ssp126, ssp245, and ssp585 scenarios, with decreases of 31.38%, 26.25%, and 45.10%, respectively. Compared with the 2050s, the total suitable area in the 2090s showed a downward trend under ssp245 and ssp585 scenarios, with decreases of 14.89% and 38.64%, respectively, while increasing significantly under the ssp126 scenario to 359,474 km^2, 22.00% higher than that in the 2050s.

Table 3 Suitable growing area of Leonurus japonicus in China, under different climate

scenarios in the future Km^2

Climate change scenarios	Unsuitable area	Low-grade suitable area	Moderately suitable area	Highly suitable area	Total suitable area
Current	7 217 667	1 202 780	1 043 933	135 620	2 382 333 (24.8%)
ssp126-2050s	7 965 319	984 512	621 481	28 687	1 634 680 (17.0%)
ssp126-2090s	7 605 845	1 025 019	886 812	82 324	1 994 154 (20.8%)
ssp245-2050s	7 842 938	1 005 601	709 608	41 853	1 757 062 (18.3%)
ssp245-2090s	8 104 496	950 041	532 745	12 717	1 495 503 (15.6%)
ssp585-2050s	8 292 514	837 216	433 948	36 716	1 307 880 (13.6%)
ssp585-2090s	8 797 452	525 523	270 647	6 377	802 547 (8.6%)

By comparing the predicted suitable areas in the 1950s and 1990s, it can be seen that there are differences in the response of *Leonurus japonicus* to climate change, and that the trends are different (Figure 4). Under the ssp585 scenario, the highly suitable area of *L. japonicus* changed the most. By the 2050s, the highly suitable area decreased by 98,904 km^2, 72.93% lower than the current area. By the 2090s, the area is reduced by 129,243 km^2, a decrease of 95.30%. Under the ssp126 scenario, the highly suitable area of *L. japonicus* in the 2090s decreased the least, being 53,296 km^2 less than the current area for a decrease of 39.30%. Under the ssp245 scenario, the highly suitable area decreased by 93,767 km^2 in the 2050s, a decrease of 69.14%. The area of the 2090s decreased by 29,136 km^2 compared with the 2050s, a decrease of 69.62%. Under the three climate scenarios, the suitable area of *L. japonicus* showed a decreasing trend, and it was most sensitive to climate change under the ssp245 and ssp585 scenarios.

In terms of spatial pattern, there were large differences in suitable migration locations of *L. japonicus* under different climate scenarios, but the overall migration trend was more consistent; the overall trend migrates northward (Figure 5). At present, the centroid of the suitable area of *Leonurus japonicus* is in Lixian County, Changde City, Hunan Province (111.43°E, 29.90°N). Under the climate scenario ssp245 in the 2090s, the center of mass of the suitable area of*Leonurus heterophyllus* would be the farthest north. At this time, the center of mass of the suitable area of *Leonurus heterophyllus*would be located in Xixia County, Nanyang City, Henan Province (111.55 ° E, 33.43 °N); the migration distance would be 391,314 m. Under the climate scenario ssp585-2090s, the movement distance of the centroid of the suitable area of *L. japonicus* to the northwest is 413,003 m, moving to Dazhu County, Dazhou City, Sichuan Province (107.23 °E, 30.68 °N). Under future climate change scenarios, global warming and humidification will cause the mass center of the suitable growing area of *L. japonicus* in China to move northward as a whole, and the migration location would trend toward further northwestward expansion.

3.4. Evaluation of environmental factors

The results of the environmental factor evaluation are shown in Table 4. The factors contributing more than

5% to the potential geographical distribution of *L. japonicus* (Zhan et al., 2022) were the lowest temperature in the coldest month (12.2%), the precipitation in the wettest month (53.8%), the precipitation in the driest month (5.7%) and altitude (20.9%). The total contribution rate of these four environmental factors was as high as 92.6%. The factors with more than 5% of the importance value were the highest temperature in the hottest month (10.6%), the lowest temperature in the coldest month (19.4%), the precipitation in the wettest month (40.3%), the precipitation in the driest month (5.8%), and the altitude (11%). The importance values of these five environmental factors were as high as 87.1%. Considering these five environmental factors as the main environmental factors, precipitation was the dominant factor.

Table 4 Contribution rate and importance of environmental variables

Environmental variable	Contribution (%)	Importance (%)
Variation coefficient of air temperature	2.3	4.2
The highest temperature in the hottest month	1.3	10.6
The lowest temperature in the coldest month	12.2	19.4
Annual range of temperature	0.2	1.7
Precipitation of the wettest month	53.8	40.3
The driest monthly precipitation	5.7	5.8
Altitude	20.9	11
Cation exchange capacity of topsoil	0.5	1.4
Electrical conductivity of topsoil	1.3	2.3
Gravel volume in topsoil	0.5	0.6
Organic carbon content in topsoil	0.8	1
Silt content in topsoil	0.7	1.7

3.5. Ecological characteristics of distribution areas

The relationship between main environmental factors and potential distribution areas is shown in Table 5. Under the three climate scenarios of ssp126, ssp245, and ssp585, the suitability of *L. japonicus* in the 2050s and 2090s was lower than that in the current period, and the decrease was greater than 0.1. Under the ssp585 scenario, the decrease in the 2090s was 0.25. In the ssp126 climate scenario, the suitability of 2090s was increased compared with the 2050s, and the growth rate was 0.01.

The minimum temperature of the coldest month and the precipitation of the wettest month of the 489 distribution points of *L. japonicus*were opposite to the changes in habitat suitability of *L. japonicus.* In the two periods of 2050s and 2090s, the three scenarios of ssp126, ssp245, and ssp585 showed increasing trends.

The maximum temperature of the hottest month in 489 distribution sites increased by 8.9%, 8.5%, and 10.8% in the 2050s under ssp126, ssp245, and ssp585, respectively. The warmest month maximum temperatures in the 2090s under ssp245 and ssp585 scenarios increased by 3.5% and 8.8%, respectively, compared to those in the 2050s.

The driest month precipitation of 489 *Leonurus artemisia*distribution points showed a downward trend in the 2050s and 2090s under the three scenarios of ssp126, ssp245, and ssp585.

Table 5 Results of the analysis of major environmental variables

Environmental variable	Current	SSP126	SSP126	SSP245	SSP245	SSP585	SSP585
		2050s	2090s	2050s	2090s	2050s	2090s
The highest temperature in the hottest month	28.24	30.74	30.25	30.64	31.71	31.30	34.06
The lowest temperature in the coldest month	-4.86	-2.78	-2.27	-1.92	-0.86	-1.72	0.04
Precipitation of the wettest month	200.15	201.14	221.75	211.76	222.73	223.84	239.43

Environmental variable	Current	SSP126	SSP126	SSP245	SSP245	SSP585	SSP585
The driest monthly precipitation	18.56	17.43	16.84	16.90	15.64	18.22	17.43
Altitude	819.36	819.36	819.36	819.36	819.36	819.36	819.36
Suitability of species habitat	0.51	0.40	0.41	0.39	0.34	0.39	0.26

3.6 Niche differentiation analysis and priority reserve planning

In Figure 6, the green and red represent the niche spaces of the future and the current periods, respectively, and the blue represents the overlapping space. The figure shows that the degree of niche differentiation in different periods of the 2050s and 2090s showed a downward trend. The niche distribution degree of population distribution in the same period of the 2050s and the 2090s showed an increasing trend. The size of niche overlap reflects the similarity of plant utilization resources. Large niche overlap indicates that they have similar ecological adaptability, resource utilization, and biological characteristics under certain environmental conditions (Yuan et al., 2021). Compared with the population distribution in the current period, the D value of the population distribution in the future period is greater than 0.6; the degree of niche overlap is large; the adaptability to habitat resources is similar, and the resource competition is fierce, so there is no significant niche differentiation. By calculating the niche breadth of *Leonurus japonicus* in each period via the ENMTools software package, the results showed that the niche breadth values of *Leonurus japonicus* in each period in the future, i.e., B1 (minimum value is 0.581) and B2 (minimum value is 0.967), are larger than those of *Leonurus japonicus* in the current period (i.e., B1 (0.543) and B2 (0.961)). This indicates that the niche breadth of*Leonurus japonicus* in each period in the future will be larger than that in the current period, and its distribution will be more extensive. There is a greater opportunity for niche overlap with the current species, and more intense competition is likely to occur in the case of limited available resources. The results are consistent with the above ecospat package analysis.

The planning of *Leonurus japonicus* priority protection areas was proposed according to the principle of maintaining ecosystem integrity and species habitat connectivity and ensuring consistent protection and management. The priority protected areas are shown in Figure 7. The map shows that priority protected areas included southeastern Anhui, southwestern Hubei, southeastern and northeastern Chongqing, southeastern Sichuan, eastern Yunnan, Guizhou, Fujian, Guangxi, southwestern Hubei, southeastern and northwestern Zhejiang, northeastern Guangdong, a small part of western Jiangxi, and a small part of the south. These places are highly coincident with the high and middle suitable areas, indicating that the modeling prediction results were accurate.

4. Discussion

4.1. Optimization of the model for predicting the current suitable area of *Leonurus japonicus*

This study used the ENMeval data package to optimize the model based on climate, topography, and soil factors. This method limits the background data to the area corresponding to the calibration location, so that the potential geographical distribution area simulated by Maxent covers the current distribution points. This method allows the adjustment of model parameters to improve the performance of the Maxent model, and then an adjustment test is performed by changing the regularization level, thereby reducing the complexity of the model. Finally, the accuracy of the model is measured by improving the fitting degree between the predicted results and the actual distribution area and by visual inspection of the geographic prediction map (Phillips et al., 2017). The Maxent model with optimized parameters can efficientlyreduce the complexity of the model, improve the fitting degree between the predicted results and the actual results, and predict the distribution of species well. The response curve becomes smooth and approach the normal distribution curve, conforming to the Shelford tolerance rule (Ouyang et al., 2019; Li et al., 2018; Phillips et al., 2017).

Leonurus japonicus grows in various habitats, mostly in areas with the sun exposure, and it can grow in general soils. It is distributed in Anhui, Fujian, Guangdong, Guangxi, Guizhou, Hainan, Hebei, Heilongjiang, Henan, Hubei, Hunan, Jiangsu, Jiangxi, Jilin, Liaoning, Inner Mongolia, Shaanxi, Shandong, Shanxi, Sichuan, Yunnan, Zhejiang, and other places (http://www.iplant.cn/info/Leonurus%20japonicus?t=f). In this research, based on the optimized maximum entropy model, the current suitable areas of *Leonurus japonicus* were predicted, and the results were consistent with the actual distribution, indicating that the Maxent model was reliable and accurate for predicting the distribution of*Leonurus japonicus* .

4.2. Restriction of Environmental Variables on Geographical Distribution of *Leonurus japonicus*

The highest temperature in the hottest month, the lowest temperature in the coldest month, precipitation in the wettest month, altitude, and precipitation in the driest month were the main environmental factors affecting the distribution of *L. japonicus* . To understand the influence of main environmental factors on the distribution of*Leonurus japonicus* , the relationship between distribution probability and ecological factors was judged according to the response curve. It was assumed that when the distribution probability of*Leonurus japonicus* was greater than 0.5, the corresponding environmental factors were suitable for plant growth (Guo et al., 2017; Jia et al., 2019). In this study, when the probability was greater than 0.5, the highest temperature range of the hottest month was 26.8–33°C, and the highest temperature of the hottest month most suitable for the growth of *Leonurus japonicus* was about 31°C. When the probability was greater than 0.5, the range of the lowest temperature in the coldest month was -8–11.5degC; the lowest temperature in the coldest month that was most suitable for the growth of *Leonurus japonicus* was about 8.3degC, a result that was consistent with the research of Wang and colleagues (Wang et al., 2015) suggesting that the suitable temperature for the growth of *Leonurus japonicus* is 22–30degC, at high temperatures above 35degC the plant grows well, and the growth is slow below 15degC. In this forecast, when the probability was greater than 0.5, the wettest monthly precipitation was in the range of 178–370 mm, and the wettest monthly precipitation that was most suitable for the growth of *L. japonicus* was about 240 mm. The most suitable altitude for the growth of *L. japonicus* was about 200 m, which fully reflects the warm and humid climate preference of *L. japonicus* and is suitable for growth below a 1000-m altitude (Wang et al., 2015).

This study shows that precipitation, topography, and temperature determine the potential geographical distribution of *Leonurus japonicus* on a certain scale. Although precipitation play an important role in the potential distribution pattern of *L. japonicus,*topography and temperature factors will also redistribute precipitation resources to a certain extent. Therefore, the effects of temperature, precipitation, and topography on the potential distribution pattern of*L. japonicus* cannot be ignored, and the interactions between these factors affect the potential distribution pattern of *L. japonicus* .

4.3. Effect of Climate Warming on Geographical Distribution of

Leonurus japonicus

Under the three shared socioeconomic pathways (SSPs) scenarios in the future, high humidity and high temperature will expand the distribution range of the suitable area of *Leonurus japonicus* to the north. Compared with the current suitable area, the 2050s shows a significant decrease, which is significantly greater than the decrease of 2090s, i.e., the decreasing trend of the suitable area of *Leonurus japonicus* will decrease, and the response to climate change was most sensitive under the ssp245 and ssp585 scenarios. Under the ssp126 scenario, the distribution of suitable areas for *L. japonicus*increased significantly, indicating that sustainable development has an important impact on biological growth and reproduction and the improvement of the ecological environment. Under different economic path change scenarios in the future, the response of the spatial pattern of the suitable area of *L. japonicus* to the change is generally consistent, i.e., with the increase of climate warming, the overall migration of the spatial location of the suitable area of *L. japonicus* becomes greater. When the shared socio-economic path is the same, except for the geometric center point of the 2090s suitable area under the ssp585 scenario, under the low-moderate socio-economic paths, the geometric center of the 2090s *L. japonicus* suitable area shows a trend of northward migration compared with the 2050s, and the migration distance is the largest under the ssp245-2090s scenario. The migration trend of *Leonurus japonicus* is consistent with the migration of species to high latitudes under the background of global warming (Liu et al., 2022).

4.4. Priority protection zoning of *Leonurus japonicus*

This study shows that the priority protection zones of *L. japonicus* in China are in the southwest of central China, south of the Five Ridges, south of eastern China, and Guizhou Province. The priority protected areas of national key protected medicinal plant species have a large area and a concentrated distribution in the southern mountains (Xie et al., 2022). This part of the region has suitable climate, light, and temperature conditions for the growth and development of most medicinal plants. In addition, the intensity of human intervention in mountainous areas is also relatively low, so the biodiversity in these areas is extremely rich. The prediction results are consistent with the above situation and are more accurate.

5. Conclusions

The default parameters of the model were optimized in this study. The results showed that the feature combination of the optimal model was fragmented, and the control rate was 1.5. The complexity of the optimized model was low; the response curve became smooth; the prediction results were consistent with the actual results; and the prediction accuracy was high. The suitable area of *L. japonicus*in China is widely distributed in the current period. Under different scenarios of shared economic paths in the future, except for the increase of the suitable area of *L. japonicus* in ssp126 in the 2090s, the suitable area of *L. japonicus* in the other scenarios shows a downward trend; the suitable area of *Leonurus japonicus*in the middle and low latitudes decreases, and the decrease will gradually increase. The effect is most sensitive under the ssp245 and ssp585 scenarios. In the context of different economic paths, there was no significant niche differentiation between the future and current suitable growing regions of *L. japonicus* . Therefore, the priority protected areas of *L. japonicus* should be set in the southwest of central China, the Lingnan area, the south of eastern China, and Guizhou Province.

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Credit authorship contributions statement

Yongji Wang: Conceptualization, methodology, software, formal analysis, investigation and writing - original draft. Liyuan Xie: Writing - review and editing, supervision, methodology and resources. Xueyong Zhou: Resources. Renfei Chen: software, writing, funding acquisition. Guanghua Zhao: Software, methodology and formal analysis. Fenguo Zhang: Funding acquisition, supervision, writing, review and editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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DATA AVAILABILITY STATEMENT

All data and analysis code will be made publicly available upon manuscript acceptance at Dryad (https://datadryad.org/stash/dashboard).

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