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Original Research

Climatic Changes in the Anthropocene Have Increased the Suitable Habitat Areas of *Paeonia delavayi* in China

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Abstract

Paeonia delavayi is a woody plant of the peony group, endemic to China, and has been a traditional medicinal herb since ancient times, as well as a valuable resource for breeding new peony species. Predicting the contemporary and future distribution patterns of *Paeonia delavayi* in suitable habitats under climate change conditions can provide scientific data to support the establishment of effective conservation. The potential distribution area of the endangered medicinal plant *Paeonia delavayi* was simulated by the Maxent model. The contribution rate of environmental factors and the knife-cut method were used to test and analyse the factors affecting the distribution of *Paeonia delavayi*. The response curves were used to determine the appropriate values of environmental factors. The AUC value for Paeonia lactiflora was 0.990, indicating excellent model accuracy. The current total suitable habitat area of *Paeonia delavayi* was 41.58×104 km^2, located in the southwest region of China. The high suitable habitat area of *Paeonia delavayi* was 3.71×104 km^2, accounting for 8.92% of the total suitable habitat area, mainly distributed in the south of Sichuan, north of Yunnan, and south of Chongqing in thin strips. The most important environmental factor affecting the geographic distribution of *Paeonia delavayi* is isothermal (Bio3). Under the future climate change scenario, the total suitable habitat area of *Paeonia delavayi* will increase significantly, and the area of highly suitable habitat will also increase. The centroid of the highly suitable area tends to migrate to high latitude and northwest direction, and the migration range is greater under the high-concentration emission scenario. The research results can provide a theoretical basis for the in-situ protection and sustainable utilization of *Paeonia delavayi*.

Keywords: *Paeonia delavayi*, suitable area, potential geographic distribution, climate change, MaxEnt

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Introduction

Among the top ten environmental problems in the world, climate change is listed as the most important issue. In the context of global climate change, the response and feedback of food crops to climate change have become one of the core research areas and focal issues [1]. Climate change irreversibly changes the ecosystem and ecological environment on which species depend. On a regional scale, agriculture depends on local climatic and ecological conditions, so the climate has become the most critical environmental factor affecting plant distribution [2-3]. Climate warming will greatly affect plants' growth and development and lead to regional changes in their climate suitability [4-5]. Related studies have shown that precipitation may continue to increase with the concentration of greenhouse gas emissions. The spatial and temporal climate patterns may change plants' geographical distribution and habitats [6]. Therefore, it is necessary to use ecological models to predict the distribution of suitable habitats for important plants, suitable cultivation areas, and environmental factors that determine the distribution of plant habitats, which is of great significance for ensuring biodiversity security.

Many commonly used species distribution models exist, such as the BIOCLIM, Domain, CLIMEX, GARP, and MaxEnt models. Due to the different theoretical foundations of the models, their simulation and prediction results vary considerably. Many studies have demonstrated that the MaxEnt model has the best simulation effect among the many species distribution models. Yang et al. analyzed the suitable distribution and conservation vacancies of isolates in China using the MaxEnt and GARP models. The results showed that the simulation effect of the MaxEnt model was significantly higher than that of the GARP model [7]. Elith et al. compared the simulation performance of various ecological niche models, and the results showed that MaxEnt had the highest prediction accuracy [8]. In 2004, the American scientist Phillips et al. developed the MaxEnt species distribution modelling software using the JAVA language, based on maximum entropy theory [9]. Since its introduction, the MaxEnt model has been widely used to predict the potential range of invasive organisms and the habitat of endangered and economically valuable species [10]. Its prediction results have been highly evaluated in the industry.

Paeonia delavayi, a woody plant of the peony group, is endemic to China and has been a traditional medicinal herb since ancient times. With its very narrow distribution area, exceptionally beautiful leaf shape, and flower colour (Fig. 1), *Paeonia delavayi* is a precious resource for breeding new peony varieties. It is classified as a Grade II protected plant by the state forestry administration of the People's Republic of China. Field surveys have shown that *Paeonia delavayi* has a natural distribution area in Sichuan Province, Yunnan Province, and the Tibetan Autonomous Region of Tibet. In addition to its oil and ornamental values, it has special medicinal values. According to the Chinese Ethnomedicinal Dictionary, Chinese Ethnomedicinal Dictionary, Chinese Pharmacopoeia, and related literature, it has unique efficacy in treating blood vomiting, blood in urine, dysmenorrhea, etc. It can also treat pain in the chest and abdomen, diarrhoea and abdominal pain, spontaneous sweating, night sweating, etc. It can also treat chest, abdomen, hypochondriac pain, dysentery abdominal pain, spontaneous sweating, and night sweats embolism. *Paeonia delavayi* is extremely responsive to climate change as an important plant resource [11-13]. *Paeonia delavayi*, as traditional Chinese medicine, has a huge market demand for its tannins and roots, leading to its wild resources being unable to meet the market demand. Therefore, driven by economic interests, continuous high-intensity and uncontrolled harvesting has led to a drastic decline in the wild resources of *Paeonia delavayi* [12, 14-15]. Investigations by numerous researchers have shown that *Paeonia delavayi* is in the endangered category and urgently needs to be saved and protected [13].

By modelling the geographic distribution of *Paeonia delavayi* from the perspective of ecological niche theory, the relationship between the geographic distribution of the target species and climate and human activities was analyzed. The effects of key environmental variables and human activities on the distribution of *Paeonia delavayi* were studied to predict the role of climate change on potential range changes. Scientific data can be provided to support the establishment of effective conservation in response to changes in *Paeonia delavayi* areas due to climate change.

The main objectives of this study are: By modelling the geographic distribution of *Paeonia delavayi* from the perspective of ecological niche theory, as shown in (Fig. 2), Scientific data can be provided to support the establishment of effective conservation in response to change in *Paeonia delavayi* areas due to climate change.

The main contributions of this study are: (1) to show the current and future distribution patterns of *Paeonia*

Fig. 1. *Paeonia delavayi* photographed from wild habitat.

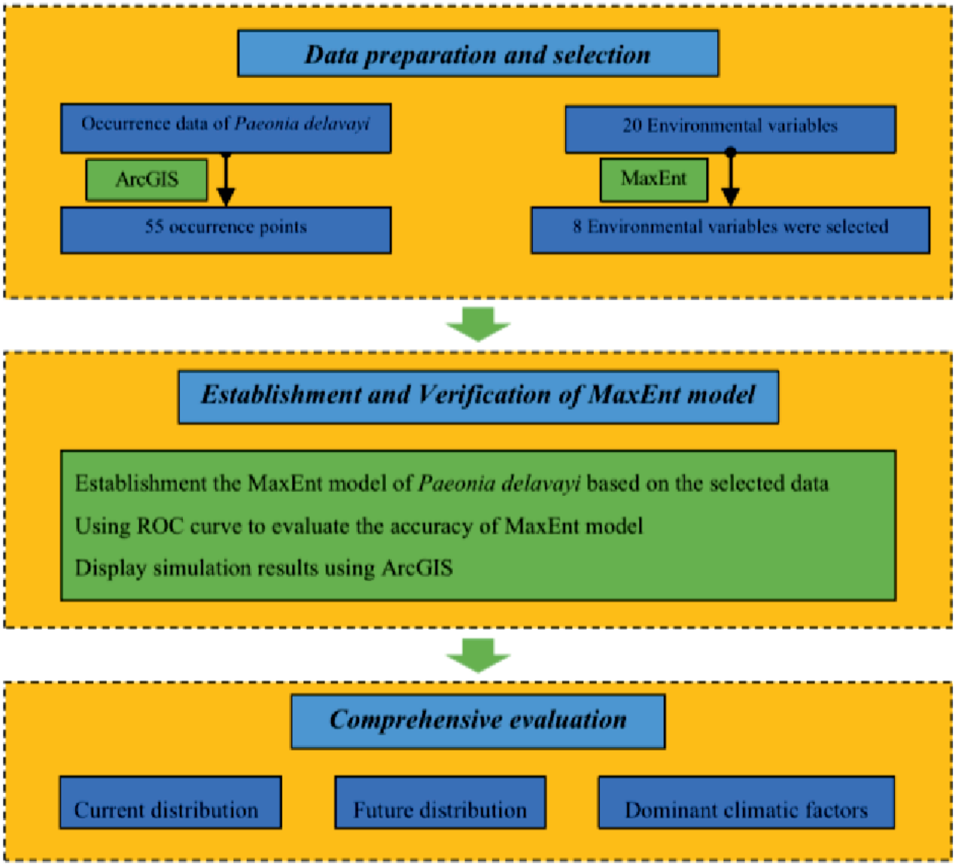

Fig. 2. Flowchart displaying the steps of the present study.

delavayi; (2) to show the potential distribution trends of *Paeonia delavayi* in the context of climate change; and (3) to investigate the response of the distribution of *Paeonia delavayi* to climate change.

Materials and Methods

Sources of Species Data

Distribution information of *Paeonia delavayi*: The distribution points of *Paeonia delavayi* come from relevant publications and literature [16-17], field surveys and the China Digital Herbarium. According to the research methods of Guan et al. [18] and Elith et al. [19], 55 effective distribution points of *Paeonia delavayi* were finally obtained (Fig. 3).

Variable Sourcing and Processing

The climate data is derived from the Worldclim database, a global climate raster based on international meteorological records, integrated with interpolated data and includes 19 bioclimatic factors. The data are spatially resolved at 2.5 arc-minutes and are available as raster files in tiff format. The Beijing Climate Centre climate system model (BCC-CSM2-MR) with coupled mode 6 (CMIP6) was selected as the future climate model after intercomparison, as the CMIP6 scenario model is closer to the real situation [20]. The Human Activity Intensity (HAI) grid, also known as the Human Footprint Index (HFI) grid, was used for the final phase of the Human Footprint Wild project in 2009 [21]. The spatial resolution of the above data is 2.5 arc-minutes. Height data (30 m) were downloaded from the Geospatial Data Cloud (GDC), and their resolution was harmonised with climate variables through kriging (2.5 arc-minutes).

Model Variable Filtering

In this study, different parameter configurations were selected for trial runs to evaluate the performance of the parameter configurations used to adjust the optimal parameters of the model. Firstly, based on the known distribution points of *Panicum millrace* and the corresponding environmental factors, RM was set to 0.5 to 4. Six feature combinations (FC) were used to optimise the model parameters to select the best parameter combinations: L (linear features), LQ (linear features + quadratic features), H (hinge features), LQH (linear features + quadratic features + hinge features), LQHP (linear features + quadratic features + product features) and LQHP (linear features + quadratic features + product features). LQHP (linear features + secondary features + hinge features + product features)

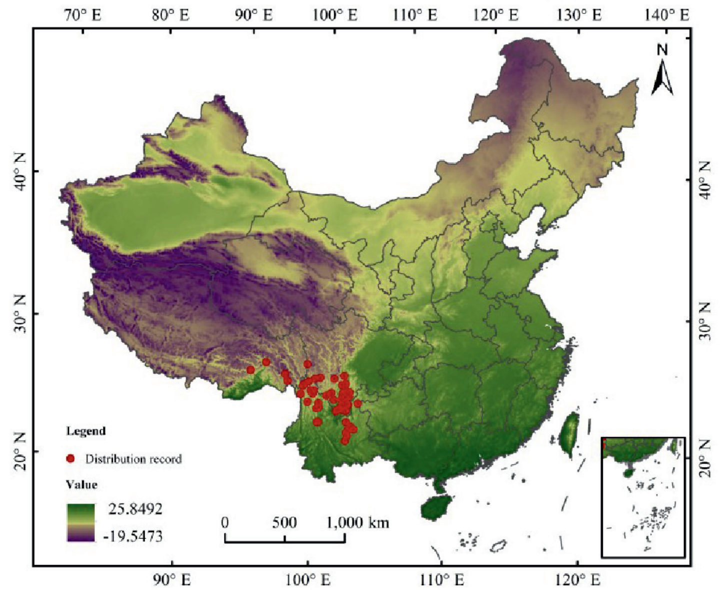

Fig. 3. Species occurrence records of *Paeonia delavayi* .

and LQHPT (linear features + secondary features + hinge features + product features + threshold features). Finally, in this study, RM is set to 1, and the feature combination is LQHPT. In the next research, machine learning should be performed to optimize the model further and improve its accuracy [22-23].

A knife-cut approach was chosen to determine the weights of each variable affecting the variables [24]. Many researchers have introduced Pearson correlation coefficients into the comparison process to screen variables to remove covariance [25-26]. This study took the following steps to filter the modelling variables. Firstly, the initial variables and species distribution data were imported into MaxEnt, and the initial contribution of each variable was calculated to remove the variables with very low assistance. Secondly, the attribute values of all remaining variables were extracted by applying ArcGIS software. Thirdly, the correlation analysis was carried out by Spearman. Fourthly, the correlation coefficients between the variables were compared. Variables with correlation coefficients above 0.80 were screened according to the ecological significance of the variables. Those that could not be determined were compared in terms of their contribution to the initial model. Eight environmental factors were finally screened for *Paeonia delavayi* (Table 1).

Model Accuracy Verification

The model's prediction accuracy was assessed based on the area of the subject's working characteristic curve. The AUC value from 0 to 1 was positively correlated with the prediction effectiveness; the closer it was to 1, the higher the prediction accuracy of the model, and vice versa. The accuracy of the model was classified as poor, fair, good, and very good, with the AUC values in the intervals of (AUC≤0.80), (0.80<AUC≤0.90), (0.90<AUC≤0.95) and (0.95<AUC≤1.00) respectively.

Model Accuracy Verification

The format conversion function of ArcGIS software was applied to convert the ASCII format file output by MaxEnt software to a Raster format file. The distribution area in each province (district or city) was calculated using the statistical analysis function of ArcGIS. The default fitness class of the MaxEnt model was divided into ten categories. According to the IPCC interpretation of the species distribution probability (P), the suitable habitats are classified as unfit, low, moderate, and highly suitable, represented by light yellow, light green, light blue, and dark blue, respectively. Their P values are in the ranges of (0.0≤P<0.1), (0.1≤P<0.3), (0.3≤P<0.6) and (0.6≤P), respectively.

Table 1. List of the environmental variables used to develop the model of *Paeonia delavayi.*

Variables	Description
Bio3	Isothermal
Bio4	Standard deviation of seasonal variation in air temperature
Bio12	Annual precipitation
Bio6	Coldest monthly minimum temperature
Altitude	Elevation
HAI	Intensity of human activity
Bio8	Wettest quarterly average temperature
Bio15	Coefficient of variation of precipitation

Results and Discussion

Dominant Influences on the Potential Habitat of *Paeonia delavayi*

Based on 55 *Paeonia delavayi* distribution records, the MaxEnt model was used to simulate and predict the potentially suitable habitats area of *Paeonia delavayi* in China. The AUC value for the *Paeonia delavayi* test set data was: 0.990, and the AUC value for the training set data was: 0.985, which can be concluded that the *Paeonia delavayi* simulation was very effective. Its ROC curve is shown in Fig. 4.

Current researchers' views on determining the number of dominant factors need to be more consistent, with the determination of dominant factors based on contribution rates being the current majority view. The environmental factors that reach a certain level are taken as the dominant chief, but the level choice is subjective, so different criteria emerge. This study selected the top four contributing environmental factors as the dominant prevailing factors. From the arithmetic results of *Paeonia delavayi*, the eight environmental factors of isothermal (Bio3), the standard deviation of seasonal temperature variation (Bio4), annual precipitation (Bio12), and coldest monthly minimum temperature (Bio6) they contributed 32.20%, 30.20%, 16.40%, and 10.80% respectively, with the cumulative value of the four reaching 89.60%. Therefore, the top four are the dominant environmental factors (Fig. 5).

The Jackknife test showed that when using a single environmental factor variable, the standard deviation of seasonal variation in air temperature (Bio4), isothermal (Bio3), annual precipitation (Bio12), and coldest monthly minimum temperature (Bio6) were the four environmental factors that had the greatest influence on the gain in formal training of Paeonia delavayi, indicating the dominance of these environmental factor

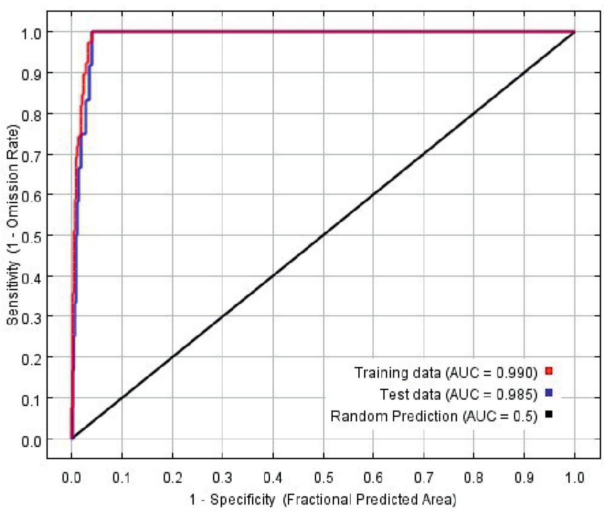

Fig. 4. Receiver operating characteristic curve of *Paeonia rockii* Maxent model.

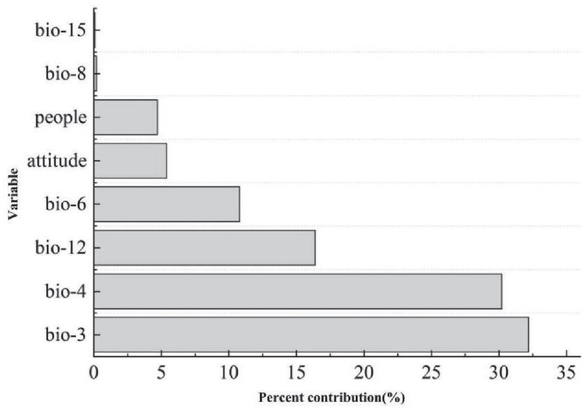

Fig. 5. Environmental variables and their contributions of *Paeonia delavayi.*

variables in governing the growth of *Paeonia delavayi* (Fig. 6).

The presence of *Paeonia delavayi* with a probability greater than 0.6 (threshold) was considered a favourable environmental factor for *Paeonia delavayi* growth and vice versa (Fig. 6). This resulted in the dominant environmental factors suitable for *Paeonia delavayi* growth being: isothermality (Bio3), the standard deviation of seasonal variation in temperature (Bio4), the minimum temperature in the coldest month (Bio6) and annual precipitation (Bio12) (Fig. 7).

Relationship between *Paeonia delavayi* and Environment Variables

The climate is a key factor in limiting the potential distribution of species at macroscopic scales, and the study of plant-climate interactions is an important direction in ecology. The MaxEnt model predicts that isothermal (Bio3), the standard deviation of seasonal temperature variation (Bio4), the minimum temperature in the coldest month (Bio6), and annual precipitation (Bio12) are the dominant environmental factors governing the potential geographical distribution of *Paeonia delavayi*. This study shows that isothermal positively affects the probability of *Paeonia delavayi* presence, suggesting that the likelihood of *Paeonia delavayi* presence is higher when there is a large temperature difference. The standard deviation of seasonal temperature variation also governs the possibility of the existence of *Paeonia delavayi*, with the probability of the presence of Paeonia delavayi increasing as the seasonal variation in temperature increases in areas suitable for the natural distribution of *Paeonia delavayi*. The likelihood of the existence of Paeonia delavayi decreases when the temperature variation continues to increase, indicating that the threshold for the survival of *Paeonia delavayi* is exceeded when the seasonal temperature variation becomes too great or too low. This suggests that seasonal cha-temperature changes are more pronounced in areas

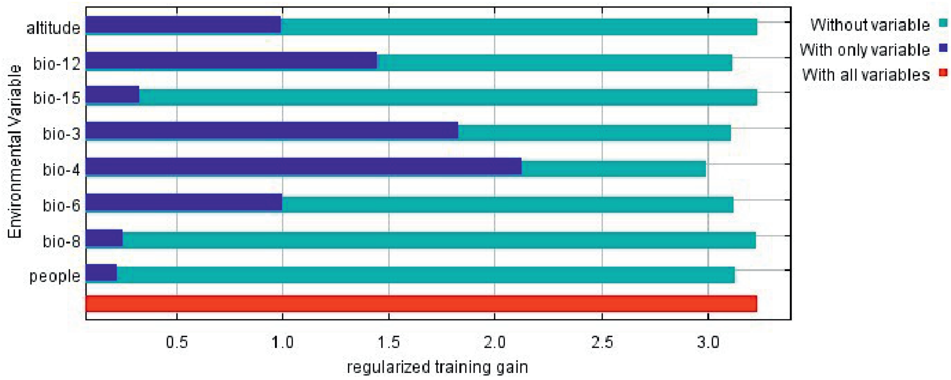

Fig. 6. The jackknife test result of environmental factor for *Paeonia delavayi.*

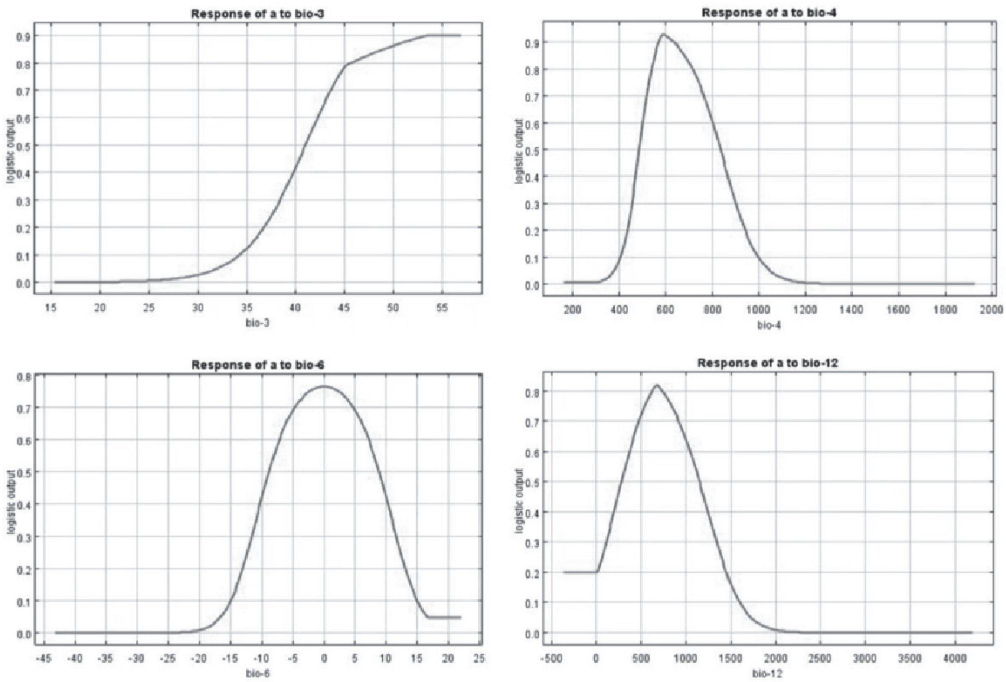

Fig. 7. Response curves of existence probalitity of *Paeonia delavayi.*

with a high probability of *Paeonia delavayi* presence. However, too drastic a change can lead to severe impacts on the growth and distribution of *Paeonia delavayi*. For example, the tropical rainforest climate's dramatic daily variation exceeding the annual variation is unsuitable for *Paeonia delavayi* survival. This is also in general agreement with the simulation results of Chen et al. [27] for *Paeonia delavayi*. Zhang et al. [17] also showed that the growth state of *Paeonia delavayi* was significantly different under different climatic conditions, which greatly impacted its growth and development. A study by Wu et al. [28] on seven protected plants in response to climate change by applying the CART model also showed that the fitness areas of plants change with increasing temperature. The plant's suitable habitats also expand with increasing precipitation. Still, some suitable habitats disappear again after reaching a threshold value, indicating that temperature and precipitation have a more important influence on the suitable habitats of the peony. The distribution of *Paeonia delavayi* is governed by the coldest monthly minimum temperature, and the probability of *Paeonia delavayi's* presence gradually increases as the minimum temperature rises. However, as the minimum temperature rises, the likelihood of *Paeonia delavayi's* company decreases. The distribution of *Paeonia delavayi* is also influenced by annual precipitation, with the possibility of the existence of *Paeonia delavayi* increasing with increasing yearly precipitation but decreasing with excessive annual precipitation. The above results suggest that temperature and precipitation strongly influence the distribution of *Paeonia delavayi*. Li et al. [15] showed that the ecological niche of *Paeonia delavayi* is tightened and may be affected by rapid changes in temperature and precipitation in the context of global climate change. Cui et al. [29] simulated the response of three medicinal plants to climate change through the MaxEnt model, showing that the area and elevation of the plant's range would change with increasing temperature and precipitation, generating new fields. However, when the plant suitability threshold was exceeded, some of the range areas disappeared again, suggesting that temperature and precipitation have a more important influence on the suitable habitats of *Paeonia delavayi*. This may also be related to *Paeonia delavayi's* cold and heat-loving, dry and waterlogged growth habits. Jiang et al. [30] modelled the response of *Paeonia delavayi* in the context of climate change. The model results showed that precipitation and temperature are the dominant environmental factors governing the distribution of *Paeonia delavayi*. And the area, elevation, and boundaries of the plant's range will change with increasing temperature and precipitation. As temperature and precipitation increase, the suitable distribution area increases. However, after rising beyond the plant's physical suitability threshold, part of the appropriate range disappears, which also indicates that temperature and precipitation have a more important influence on the habitat of *Paeonia delavayi*.

This study predicts the potential geographic distribution of *Paeonia delavayi* in China and identifies the environmental variables that limit the potential geographic distribution. Changes in the study area may have led to changes in the range of environmental factors restricting growth. Other environmental factors (e.g. vegetation cover data) also influenced the potential geographic distribution of *Paeonia delavayi*. Other environmental factors were not included in predicting the potential geographic distribution of *Paeonia delavayi* because it was impossible to predict global vegetation cover in future periods accurately. Therefore, the possible geographic distribution area obtained in this study may be partially unsuitable for *Paeonia delavayi* and must be applied in practice concerning local hydrogeological conditions.

Potential Distribution of *Paeonia delavayi*

The model for predicting the potentially suitable habitats areas of *Paeonia delavayi* was well-fitted. The possible suitable habitats of *Paeonia delavayi* under current climatic conditions are shown in Fig. 8. *Paeonia delavayi* is located in southwest China, with a total suitable habitat area of 41.58×10^4 km^2 (Table 2). The highly suitable habitats accounted for 8.92% of the total suitable area, with an area of 3.71×10^4 km^2 (Table 2), and were mostly distributed in thin strips in the southern Sichuan, northern Yunnan, and southern Chongqing regions. At the same time, another part was scattered in northwest Qianhai and southeast Tibet (Fig. 8). The moderately suitable habitats area accounts for 40.86% of the total suitable habitats area, with an area of 16.99×10^4 km^2 (Table 2), mainly surrounded by the periphery of the highly suitable habitats area in a pie-shaped distribution, concentrated in southern Sichuan, northern Yunnan, and most areas of Chongqing, and partly distributed in thin strips in western Sichuan, southeastern and south Tibet (Fig. 8). The area of low suitable habitats accounts for 50.22% of the total suitable habitats area, with an area of 20.88×10^4 km^2 (Table 2), mainly surrounded by the periphery of the moderately suitable habitats area in a pie-shaped distribution, concentrated in southern Sichuan, northern Yunnan, and southern Chongqing, and sporadically distributed in western Sichuan, northwest Guizhou, southeast and south Tibet (Fig. 7). More than half of the total suitable habitats area is covered. In all, the highly suitable habitats of *Paeonia delavayi* were distributed in thin strips in the southern Sichuan, northern Yunnan, and southern Chongqing regions, which is in good agreement with its actual distribution.

The Current Potential Range of *Paeonia delavayi*

Over the last few decades, global climate research has gained increasing importance in scientific research [31-32]. Ecologists have become aware of the great harm caused by biodiversity loss and have made ecological conservation a hot topic in environmental research. The present study analysed the distribution of *Paeonia delavayi* in potentially suitable habitats areas in China. The study showed (Fig. 8) that the habitat of *Paeonia delavayi* is located in southwest China, with a total area of 41.58×10^4 km^2 (Table2), of which 3.71×10^4 km^2

Table 2 Suitable areas for *Paeonia delavayi* under different climate change scenarios (104 km2).

Periods	Highly suitable habitat	Moderately suitable habitat	Poorly suitable habitat	Total suitable habitat
Current	3.71	16.99	20.88	41.58
2050 SSP1-2.6	10.23	20.45	22.74	53.42
2050 SSP2-4.5	7.32	22.16	23.81	53.29
2050 SSP5-8.5	12.33	18.53	20.04	50.9
2070 SSP1-2.6	6.40	19.41	21.47	47.28
2070 SSP2-4.5	8.31	21.19	24.76	54.26
2070 SSP5-8.5	16.62	26.82	24.76	68.2

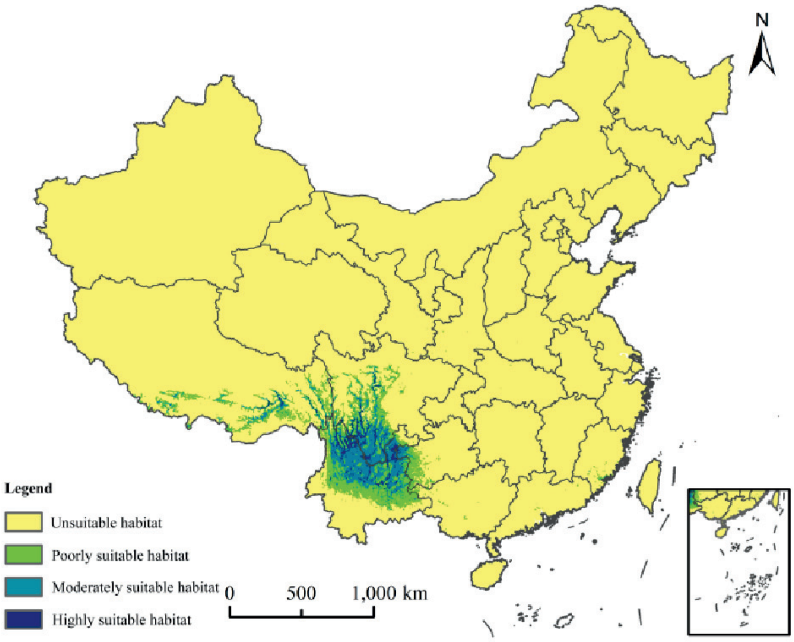

Fig. 8. Potential geographical distribution of *Paeonia delavayi* under modern climate conditions.

is highly suitable habitats (Table 2), mostly distributed in thin strips in southern Sichuan, northern Yunnan, and southern Chongqing, and sporadically in northwest Guizhou (Fig. 8). It is also scattered in northwest Qianhai and southeast Tibet (Fig. 8). Based on the data from field surveys, literature, and plant specimen databases, it was shown that *Paeonia delavayi* was distributed in northern Yunnan, southeastern Tibet, and southern Sichuan. The areas mentioned above were all within the suitable habitat areas predicted in this study. According to Gong et al. [16] and Zhang et al. [17], *Paeonia delavayi* is distributed in northern Yunnan. According to Chen et al. [27], *Paeonia delavayi* is distributed north of Yunnan and in southeastern Tibet. It is also within the suitable habitats area predicted by the study, further illustrating the prediction results' accuracy.

Impacts of Future Climate Change on the Geographical Distribution of *Paeonia delavayi*

Under the three SSPs (SSP1-2.6, SSP2-4.5, and SSP5-8.5), the highly suitable habitats area of *Paeonia delavayi* increased significantly in the 2050s and 2070s, with the greatest increase occurring in the 2070s. In the SSP5-8.5 scenario, the highly suitable habitats area increased by 347.99%, with the least growth in the 2070s. In the SSP1-2.6 method, the highly suitable habitats area increased by 72.51%, and the moderately suitable habitats area of *Paeonia delavayi* had some increase in the 2050s and 2070s. The low and rather suitable habitat areas of *Paeonia delavayi* increased to some extent in the 2050s and 2070s. The low suitable habitats area of *Paeonia delavayi* increased to varying degrees in all scenarios except for a slight decrease in the 2070s under the 2070 SSP5-8.5 scenario, indicating that climate change had a significant impact on the highly suitable habitats area of *Paeonia delavayi*. The total suitable habitat of *Paeonia delavayi* increased to some extent in the 2050s and 2070s, indicating that in addition to the conversion of some of the low suitable habitats to highly suitable habitats, many new suitable habitats have emerged, especially the highly suitable habitats (Fig. 9, Table 2). Compared to the current distribution, the total suitable habitats area would increase by 28.48%, 28.16% and 22.41% under the three SSPs (SSP1-2.6, SSP2-4.5 and SSP5-8.5) in the 2050s. The highly suitable habitats area would increase by 175.74%, 97.30% and 232.35%, respectively. The moderately suitable habitats area would increase by 20.36%, 30.43% and 9.06%, respectively. The low suitable habitats area would increase by 8.91% and 14.03% under the SSP1-2.6 and SSP52-4.5 scenarios in the 2050s and decreasing by 4.5% under the SSP5-8.5 scenario, falling by 4.02% (Table 2). Compared to the current distribution, the total suitable habitats area would increase by 13.71%, 30.50%, and 64.02% under the three SSPs (SSP1-2.6, SSP2-4.5, and SSP5-8.5) in the 2070s. The area of highly suitable habitats will increase by 72.51%, 123.99%, and 347.99%, respectively. Moderately suitable habitats will increase by 14.24%, 24.72%, and 57.86%, respectively. The area of low suitable habitats would increase by 2.83%, 18.58%, and 18.58%, respectively (Table 2).

In summary, the highly suitable habitats area of *Paeonia delavayi* shows a significant increase under future climate change scenarios, and the medium and low suitable habitats areas show an overall increasing trend. The increase in the highly suitable habitats area in the 2050s and 2070s is very significant for all

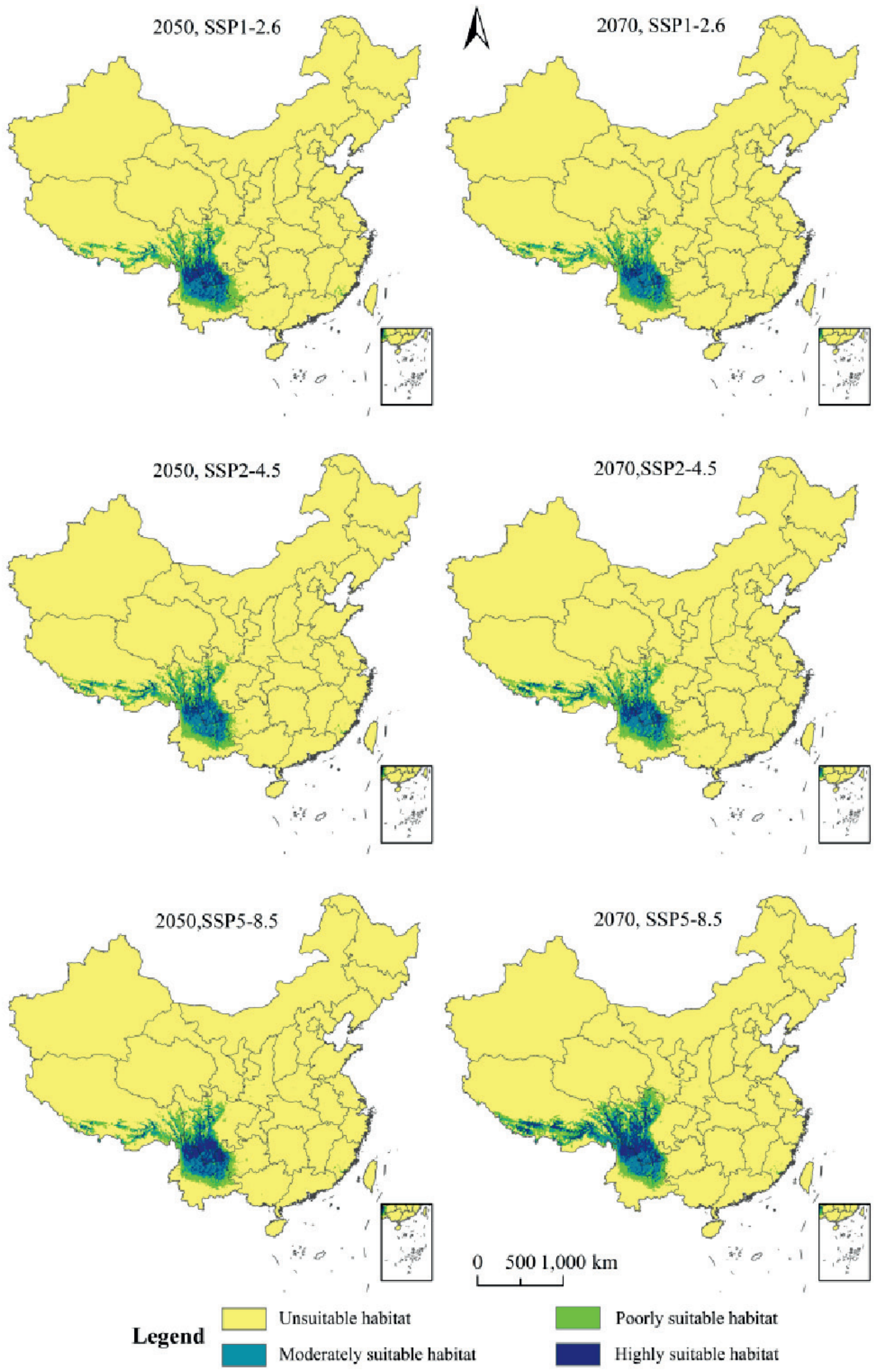

Fig. 9. Potential geographical distribution of *Paeonia delavayi* under future climate change scenarios .

three SSPs (SSP1-2.6, SSP2-4.5 and SSP5-8.5), and the highest increase in the highly suitable habitats area is over 347%, which is more than four times the current highly suitable habitats area is more than four times the current.

Changes in the Potential Geographical Distribution of *Paeonia delavayi* under Future Climate Change Scenarios

In this paper, the potential geographical distribution of *Paeonia delavayi* under three future emission scenarios with different concentrations (SSP5-8.5, SSP2-4.5, SSP1-2.6) was predicted by the MaxEnt model using environmental factors combined with current climatic conditions. The potential distribution of *Paeonia delavayi* under three future emission scenarios with different concentrations was derived by spatially overlaying the two (Fig. 10).

In the potential geographic distribution of *Paeonia delavayi* over the next two time periods, the low suitable habitats area increased in all scenarios except for a slight decrease in the 2070s under the SSP5-8.5 scenario (Fig. 10). Under the high emissions scenario

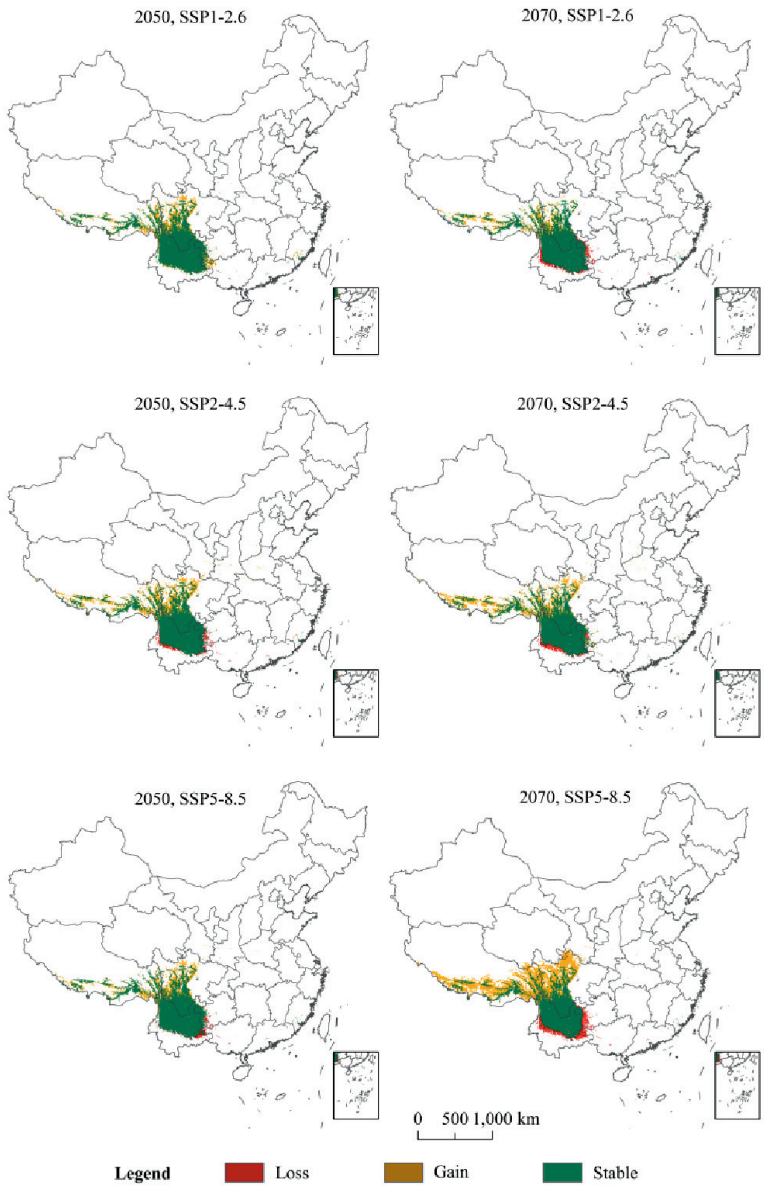

Fig. 10. Changes in the potential geographical distribution of *Paeonia delavayi* under climate change scenarios.

in the 2050s and 2070s, the *Paeonia delavayi* highly suitable habitats area increased significantly, by 232.35% and 347.99%, respectively (Table 3), indicating that the seasonal variation in temperature in many areas was more pronounced under the high emissions scenario, but the variation was not dramatic. This suggests that the seasonal variation in temperature in many places is more pronounced but less dramatic under high-emission scenarios and that many suitable habitats areas of *Paeonia delavayi* have emerged. With climate change, the standard deviation of isothermal and seasonal temperature changes in many new regions is within the survival threshold for *Paeonia delavayi*, increasing the probability of its presence. In the other emission scenarios, the isothermal and seasonal temperature variation criteria are relatively less in the suitable habitats area for *Paeonia delavayi* to survive, so the highly suitable habitats area increases significantly in the high-concentration emission scenario, which is also consistent with the simulation results of Chen et al. [17], also showed that the growth state of *Paeonia delavayi* was significantly different under different climatic conditions, which had a great impact on its growth and development [33]. In exploring the potential geographic distribution of the relict plant Cyathea in China, Zhang et al. [34] showed that the species migrates towards different latitudes as the climate warms. In the present study, *Paeonia delavayi* also moved to higher latitudes under different emissions concentrations, consistent with the above findings. As with other species, *Paeonia delavayi* in this study is compatible with a trend of partial addition and loss of potential geographic range, as well as a shift in potential geographic distribution under the influence of warming. Thomas et al. [35] showed that some species would become extinct in a warming context but that a large proportion of species will

Table 3. Future changes in suitable habitat area of *Paeonia delavayi* under climate change scenarios (10^4 km^2).

Periods	Loss	Gain	Stable
2050 SSP1-2.6	0.19	11.91	41.41
2050 SSP2-4.5	2.00	13.95	39.44
2050 SSP5-8.5	1.45	10.90	40.06
2070 SSP1-2.6	2.66	8.58	38.77
2070 SSP2-4.5	2.17	15.06	39.30
2070 SSP5-8.5	5.03	32.39	36.19

develop their growth and distribution to varying degrees during this period, suggesting that warming is a double-edged sword for the growth and distribution of species and that *Paeonia delavayi* will develop its development and distribution well in a warming context. It is clear from the projections that in the future. However, some areas will no longer be suitable for *Paeonia delavayi*; more new places will emerge that will be suitable for *Paeonia delavayi*. Far more new areas will occur than will be lost, suggesting that *Paeonia delavayi* will not be at risk of extinction for some time.

The projections show that *Paeonia delavayi* has the largest loss and gain of habitat in the 2050s under the medium concentration scenario, with 2.00×10^4 km^2 and 13.95×10^4 km^2, respectively. In the 2070s, the greatest habitat loss and gain under the high emissions scenario were 5.03×10^4 km^2 and 32.39×10^4 km^2, respectively (Table 3). Although the future climate scenario shows an increasing trend in the area of *Paeonia delavayi's* habitat, the total area is still very small, so it is still important to enhance the protection of *Paeonia delavayi*. In the low emission scenario, the loss of *Paeonia delavayi* habitat in the 2050s is mainly in western Qian. The increase in habitat is primarily in southeastern Tibet, west Sichuan, and central Sichuan. In the 2070s, the loss of *Paeonia delavayi* habitat in west Guizhou, southwestern Qian, and central Yunnan was significantly new compared to the 2050s, and the extent of the new habitat tended to decrease. In the mid-intensity emission scenario, the loss of *Paeonia delavayi* habitat in the 2050s was mainly in southwest Guizhou and central Yunnan. The increase in habitat was mainly in southeast Tibet, west Sichuan, and central Sichuan. In the 2070s, the loss of suitable habitats areas was about the same as in the 2050s, with an increasing trend in the loss of suitable habitats areas and the addition of suitable habitats areas. In the high-emission scenario, the loss of *Paeonia delavayi's* habitat in the 2050s was mainly in southwest Guizhou and east Yunnan. The habitat gain was mainly in southeast Tibet, west Sichuan, and central Sichuan. In the 2070s, the loss of *Paeonia delavayi's* habitat was evident in the southwestern part of Guizhou and the central part of Yunnan compared to the 2050s, with an increasing trend in the extent of the new habitat (Fig. 10). In terms of latitudinal variation, the general shift of *Paeonia delavayi* towards the northwest at higher latitudes may also be related to the fact that *Paeonia delavayi* prefers cold to heat and dry to water-logged growth habits. According to Li et al. [17], the ecological niche of *Paeonia delavayi* may also be affected by rapid changes in temperature and precipitation in the context of global climate change. Liu et al. [36] used the Maxent model to simulate the response of *Paeonia delavayi* to climate change, showing that the area and elevation of the plant's range would change with increasing temperature, and the plant's response to climate change was simulated by Liu et al. Huang et al. [1] explored the potential habitat of Dipteronia sinensis and showed that the suitable distribution areas of plants are strongly influenced by climatic variables such as temperature and precipitation and will change with changes in these variables, with some habitat areas disappearing and some new habitat areas emerging. Yang et al. [37] showed that temperature, precipitation, and their variation are the main environmental factors governing Xikang Yucca, further illustrating the study's accuracy.

As one of the most important environmental issues, global climate change significantly impacts plants' ecological characteristics and geographic distribution patterns. This impact will increase in the coming period [38]. Climate change is already threatening global biodiversity, with varying degrees of impact on the spatial structure and suitable distribution of plants and on intra- and inter-species relationships [39]. Studies have shown that changes in the spatial and temporal patterns of climate may lead to changes in the geographical distribution of plants, putting their original habitats at risk [40-41]. To mitigate the effects of climate change on ecosystems, we used species distribution modelling to effectively identify conservation strategies to determine the areas where sensitive species are present or likely to be present [42]. It is important to systematically investigate the geographical distribution of *Paeonia delavayi* in the context of climate change.

Climate change indirectly affects the population composition and distribution of *Panicum milliaceum* by affecting ecosystems. The environmental factor variables in this study only considered two time periods, 2050 and 2070. Future work could examine general trends in potential geographic distributions over multiple periods and use machine learning to improve model accuracy further [23, 43].

Conclusion

At present, the suitable habitats of *Paeonia delavayi* are located in the southwestern provinces, and its highly suitable habitats are mostly distributed in thin strips in southern Sichuan, northern Yunnan and southern Chongqing, with an area of 3.71×10^4 km^2, accounting for 8.92% of the total suitable habitat area. Isothermal is the most important environmental variable affecting the geographical distribution of *Paeonia delavayi*, and the dominant environmental factors are the isothermal, standard deviation of seasonal variation of air temperature, annual precipitation, and coldest monthly minimum temperature, with a cumulative value of 89.60%. Under future climate change scenarios, the suitable habitats area of *Paeonia delavayi* and the highly suitable habitats area tend to increase. In general, *Paeonia delavayi* tends to expand towards higher latitudes and to the northwest and to develop more under the high-concentration emission scenarios.

Author Contributions

X-M.H. planned and supervised the project. C.Z. performed the experiments, analysed the data, and contributed reagents/materials/analysis tools. K.C. contributed to data collection and evaluation. Y.H. revised the manuscript.

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Competing Interests

The authors declare no competing interests.

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