Pol. J. Environ. Stud. Vol. 34, No. X (2025), 1-13
DOI: *10.15244/pjoes/188894* ONLINE PUBLICATION DATE:

Original Research

Distributional Response of *Paeonia Decomposita* to Climate Change and Conservation Strategies

Mei Liu[1#], Miao-Miao Su[2#], Kai Cai[3], Pei-Sen Qi[4], Wei Gong[4], De-Chao Chen[4], Li He[4], Hua-Wei Wu[4], Dong-Zhou Deng[4], Yi Huang[5*]

[1]Ecological Security and Protection Key Laboratory of Sichuan Province, Mianyang Normal University, Mianyang 621000, Sichuan, China
[2]Tibet Autonomous Region Science and Technology Information Institute, Lhasa 850000, Tibet, China
[3]Beichuan Qiang Autonomous County Committee of the Chinese People's Political Consultative Conference, Mianyang, 621000, China
[4]Sichuan Academy of Forestry Sciences, Chengdu 610084, Sichuan, China
[5]College of Ecology and Environment, Tibet University, Lhasa 850000, Tibet, China

Received: 31 August 2023
Accepted: 19 May 2024

Abstract

Paeonia decomposita (*P. decomposita*) belongs to the peony group of woody plants and can be used to cultivate new peony varieties and as traditional Chinese medicinal medicine. With the increasing demand for *P. decomposita* in the herbal market, it is endangered and in urgent need of conservation. In this study, the potential distribution area of *P. decomposita* was simulated by the Maxent model. The environmental factors affecting the distribution of *P. decomposita* were analyzed by applying the environmental factor contribution rate and knife-cut test, respectively.

The results showed that the AUC value of the *P. decomposita* training set data was 0.949, indicating that the model was accurate. Currently, *P. decomposita*'s highly suitable areas are mainly distributed in Ganzi and Aba Prefectures in a strip-like manner, and the other part is sporadically distributed in Diqing Tibetan Autonomous Prefecture and Changdu City, with an area of 1.56×10^4 km^2, accounting for 7.10% of the total suitable areas, and the most important environmental factor for its geographic distribution is the altitude. Under the backdrop of future climate change, the areas of suitable *P. decomposita* all showed an increasing trend. Among them, high and medium suitable areas showed a significant increase in area and were strongly affected by climate change. *P. decomposita*'s highly suitable areas migrated in different latitudes and directions, and the migration span was larger under the high-concentration emission scenario. This study provides a scientific basis for the promotion, cultivation, and conservation of *P. decomposita* by predicting its potential geographic distribution and clarifying its ecological requirements.

Keywords: climate change, distributional response, *P. decomposita*, Maxent, conservation strategies

#These authors had equal contribution in the preparation of this article
*e-mail: hyhy1232021@163.com

Introduction

Global climate change poses a significant threat to the sustainable utilization of medicinal plants, and the habitats of medicinal plants will be significantly reduced or relocated under the impacts of climate change [1, 2]. The use of climatic data to construct species distribution models is a widely used approach to studying the response of medicinal plants to climate change [3, 4]. On the other hand, environmental factors have a significant effect on the accumulation of chemical constituents in medicinal plants [5, 6, 7], and studies have shown that the chemical content of medicinal plants is related to habitat suitability [6, 8]. Suitable habitats for medicinal plants are also recognized as a prerequisite for the accumulation of active ingredients [7], with plants growing in the most suitable habitats exhibiting higher levels of chemical constituents [7, 8]. The mechanisms by which climate change affects the quality of medicinal plants are not yet revealed, but the results of these studies may be useful in assessing the future geographic distribution of quality medicinal plants.

The MaxEnt (Maximum Entropy Model) model is an ecological niche model constructed on the Java platform based on maximum entropy theory. It is modeled based on species distribution points and is less affected by the number of species distribution points and the correlation of environmental factors. The MaxEnt model predicts better when modeling species distributions and is well-suited for species distribution modeling [9]. In recent years, the application of the MaxEnt model has been expanding. The study of potentially suitable habitats for endangered plants has also gradually become a hot spot [10, 11]. Based on the prediction results and in conjunction with ArcGIS, researchers can identify sites with high ecological stability for endangered plants, infer the potential geographic distribution of endangered plants, and specify different classes of potentially suitable habitats [3, 6, 12]. By employing the MaxEnt model and ArcGIS to predict the potential geographical distribution of endangered plants and medicinal plants, decision-makers can effectively forecast the impact of climate change on these species and propose appropriate strategies to establish effective conservation and utilization mechanisms.

P. decomposita (*Paeonia decomposita*) is a deciduous subshrub of the genus Paeonia in the Paeoniaceae family (Fig. 1) and is listed as endangered (EN) on the IUCN Red List of Threatened Species [13, 14, 15]. The root bark of *P. decomposita* is used as medicine, especially in traditional Chinese medicine and ethnomedicine [16]. Additionally, its special leaf shape and flower color are valuable resources for breeding new peony varieties [17]. Studies have shown that non-climatic factors govern short-term biological changes in plants, but climate change has irreversible effects on their life systems [18, 19]. As a medicinal plant, *P. decomposita* represents a special plant resource, and its growth, development, and distribution are influenced by climate change. Therefore, utilizing the MaxEnt model to comprehensively analyze the impact of environmental factors on the distribution of *P. decomposita* and employing GIS software to categorize suitable areas for *P. decomposita* can provide the scientific basis for the development of field protection for *P. decomposita* and the rational selection of field release and planting sites.

Materials and Methods

Sources of Species Data

In this study, the geographical coordinates of *P. decomposita* were confirmed and filtered by accessing the National Plant Specimen Resource Center (NPSRC) and conducting surveys on forest genetic resources. Non-specific or repetitive distribution records were eliminated. Concentrated distribution data in certain regions can lead to overfitting of the model, resulting in uncertainty. Buffer tools in ArcGIS 10.2 were employed to establish a buffer zone with a radius of 5 km around each distribution point, based on the resolution of environmental variables, ensuring that only one distribution point was retained within a 5 km radius. In total, 37 distribution points of *P. decomposita* were collected, and a distribution map was created (Fig. 1).

Sources of Environmental Variables

The climate and environmental data in this study were obtained by accessing the WorldClim database (http://www.world-clim.org/), which utilized a WGS84 coordinate system with a grid size of 2.5′. Human activity intensity (HAI) data grids were acquired from the "Human Footprint" dataset of 2009 [20]. Future climate data were generated using the BCC-CSM2-MR climate system model developed by the National Climate Center, incorporating three emission scenarios (SSP5-8.5, SSP2-4.5, SSP1-2.6). These SSPs provide more scientifically descriptive predictions of future climate change outcomes [21]. Due to the intercorrelation between environmental variables, a correlation analysis was performed on the environmental factors before incorporating them into the MaxEnt model [22, 23]. In this study, Spearman correlation analysis was conducted on the environmental factors, and when the correlation coefficient between the two factors exceeded 0.8, the one with a higher contribution rate was retained. Ultimately, seven environmental factors were selected for the operation of the MaxEnt model (Table 1).

Model Construction and Evaluation

Regarding the research methods of Hao et al. and Yang et al. [22, 23], the distribution data of *P. decomposita* and environmental factor data were separately imported into the MaxEnt software for modeling calculations. The parameter settings included

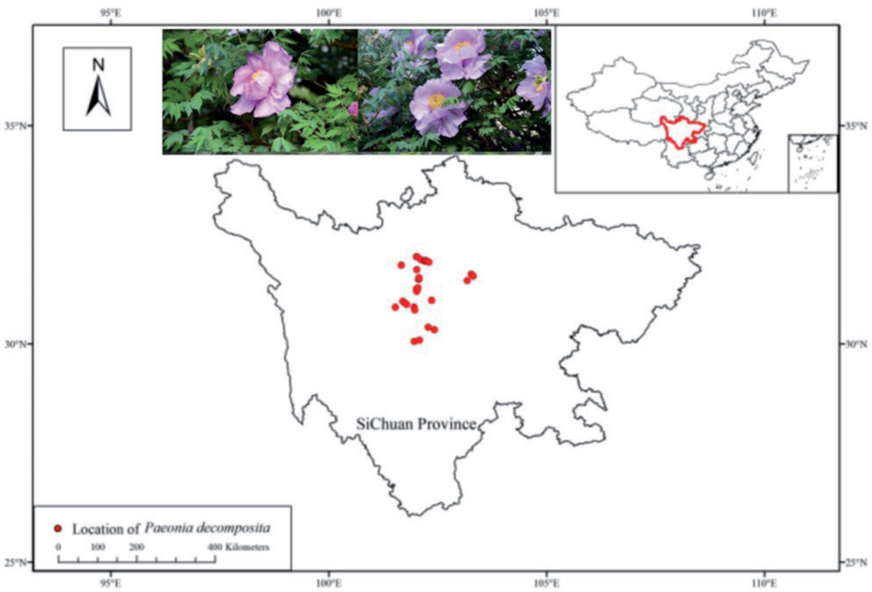

Fig. 1. Field photographs and sample distribution records of *P. decomposita.*

Table 1. Environmental variables involved in *P. decomposita* modeling operations and their contribution rates.

Variables	Description	Description	Percent contribution (%)
Altitude	Elevation	Reflecting on the effects of altitude	32.50
Bio11	The average temperature of the coldest quarter	Reflecting the effects of temperature extremes	25.40
Bio12	Annual precipitation	Reflects the amount and seasonal distribution of rainfall	23.00
Bio4	The standard deviation of seasonal variation in air temperature	Reflects average temperature and its variability	11.40
Bio3	Isothermal	Reflects temperature difference characteristics	3.50
HAI	The intensity of human activity	Reflects cumulative human pressures on the environment	2.90
Bio15	Coefficient of variation of precipitation	Reflects the amount and seasonal distribution of rainfall	1.30

allocating 25% of the distribution points as the test set and 75% as the training set. The MaxEnt model requires users to specify a set of parameters, namely the percentage of training presence (i.e., the proportion of locations used for model development and internal testing), the number of background points, clamping (i.e., whether to limit predictions within the range of variability of the input predictor variables), and the regularization multiplier (i.e., to prevent excessive overfitting of the response curve). When using species distribution models to predict species distribution, there is often an issue of overestimation or underestimation, namely false positives and false negatives. Therefore, it is crucial to evaluate the accuracy of the model simulations using effective evaluation metrics as an important step in determining model accuracy and usability [24]. In this study, the prediction accuracy of the model was assessed using the area under the curve (AUC) of the receiver operating characteristic (ROC) curve [25]. A higher AUC value indicates better predictive performance of the model, and the evaluation criteria are detailed in Table 2 [3].

Classification of Potentially Suitable Areas

Choose the average of 10 repetitions as the simulated result for this study in the output file. This result is generated based on the logical values (P) representing the probability of species presence, with P ranging from 0 to 1. A higher P value indicates a greater likelihood of species presence. Use ArcGIS 10.2 software to convert the predicted results into raster format and perform classification and visualization on suitable habitats. Based on the P values, employ the natural breakpoints method to divide the suitable habitats into four levels (Table 3)[2]. Calculate the number of cells in each level

Table 2. Relationship between AUC and the accuracy of the model.

AUC value range	Model Accuracy Class
AUC≤0.80	Poor
0.8<AUC≤0.90	Ordinary
0. 90<AUC≤0. 95	Good
0.95<AUC≤1.00	Excellent

Table 3. Range of *P*-values for different suitable habitat areas classes.

P-value range	Suitable habitat areas classes
0.6≤*P*≤1.0	Highly suitable habitat areas
0.3≤*P*<0.6	Medium suitable habitat areas
0.1≤*P*<0.3	Low suitable habitat areas
0.0≤*P*<0.1	Unsuitable habitat areas

and determine the proportion of suitable habitat area for each level.

Determination of Dominant Environment Variables

The determination of the dominant factors remains a topic of debate among scholars. Most researchers identify dominant environmental factors based on the cumulative contribution rate, considering environmental factors with cumulative contribution rates exceeding a specific threshold as the primary environmental factors. This threshold is typically subjectively chosen based on the characteristics of the studied species and research findings, leading to varying standards. In this study, the top four contributing environmental factors were selected as dominant environmental factors [8]. The results were also examined by the Jackknife method to determine which environmental factor variables influenced the formalized training gains the most when only a single environmental factor variable was used [10].

Results and Discussion

Evaluation of Model Accuracy

Based on the distribution records of *P. decomposita*, the potentially suitable habitats of *P. decomposita* in China were simulated and predicted using the MaxEnt model. The AUC value for the test dataset of *P. decomposita* was 0.929, and the AUC value for the training dataset was 0.949, indicating a "good" performance of the *P. decomposita* simulation. The ROC curve, as shown in Fig. 2, illustrates that the model was appropriately designed and that the predicted results are highly reliable, making them suitable for subsequent analysis.

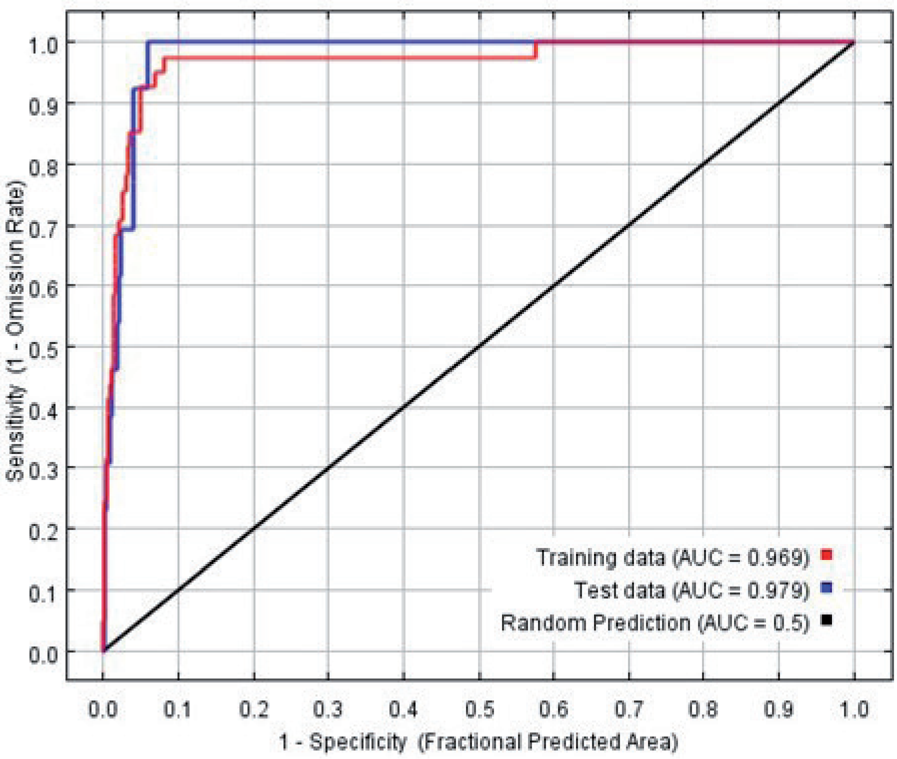

Fig. 2. Receiver operating characteristic curve of *P. decomposita* Maxent model.

Potential Distribution and Suitability Evaluation of *P. Decomposita*

Fig. 3 and 4 display the results of the model's prediction for the potentially suitable habitats of *P. decomposita*. The analysis reveals that the current suitable habitats for *P. decomposita* are primarily concentrated in a linear pattern within the southwestern region of Sichuan, covering a total area of 21.97×10^4 km^2 (Fig. 3, 4 and 5a). The high suitability zone occupies 7.10% of the total suitable habitat area, spanning 1.56×10^4 km^2, with a narrow distribution in Ganzi and Aba prefectures, along with scattered patches in Diqing prefecture and Changdu region (Fig. 3, 4 and 5a). The moderate suitability zone accounts for 26.17% of the total suitable habitat area, covering 5.75×10^4 km^2. It mainly surrounds the high suitability zone in a linear pattern, with a concentrated distribution on the outskirts of Ganzi and Aba prefectures, and sporadic occurrences in Changdu region, Diqing prefectures, and Shaotong city (Fig. 3, 4, and 5a). The low suitable habitat area occupies 66.73% of the total suitable habitat area, amounting to 14.66×10^4 km^2. It is primarily located along the outer edges of the moderate suitable habitat

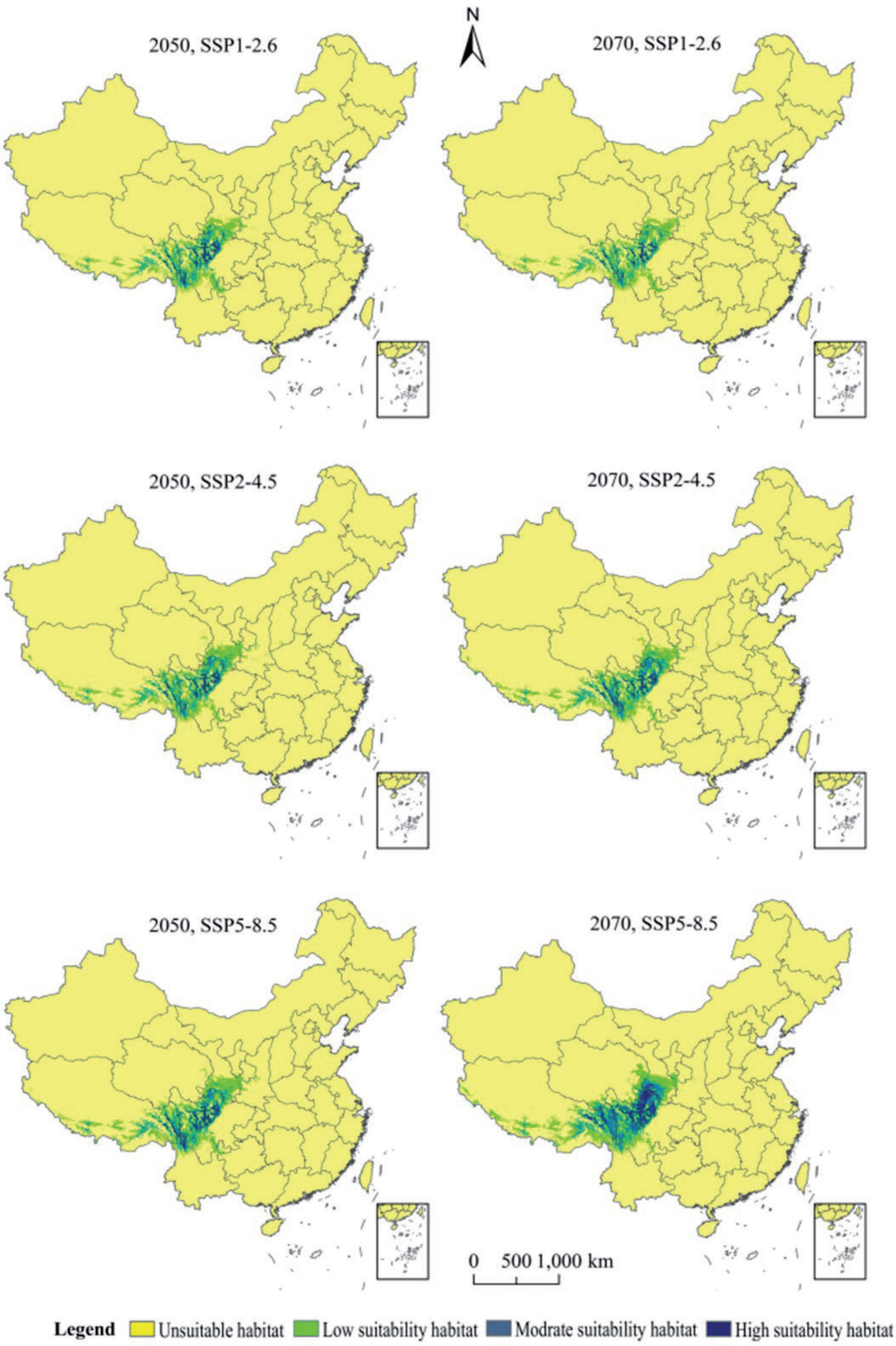

Fig. 3. Potential geographical distribution of *P. decomposita* under future climate change scenarios.

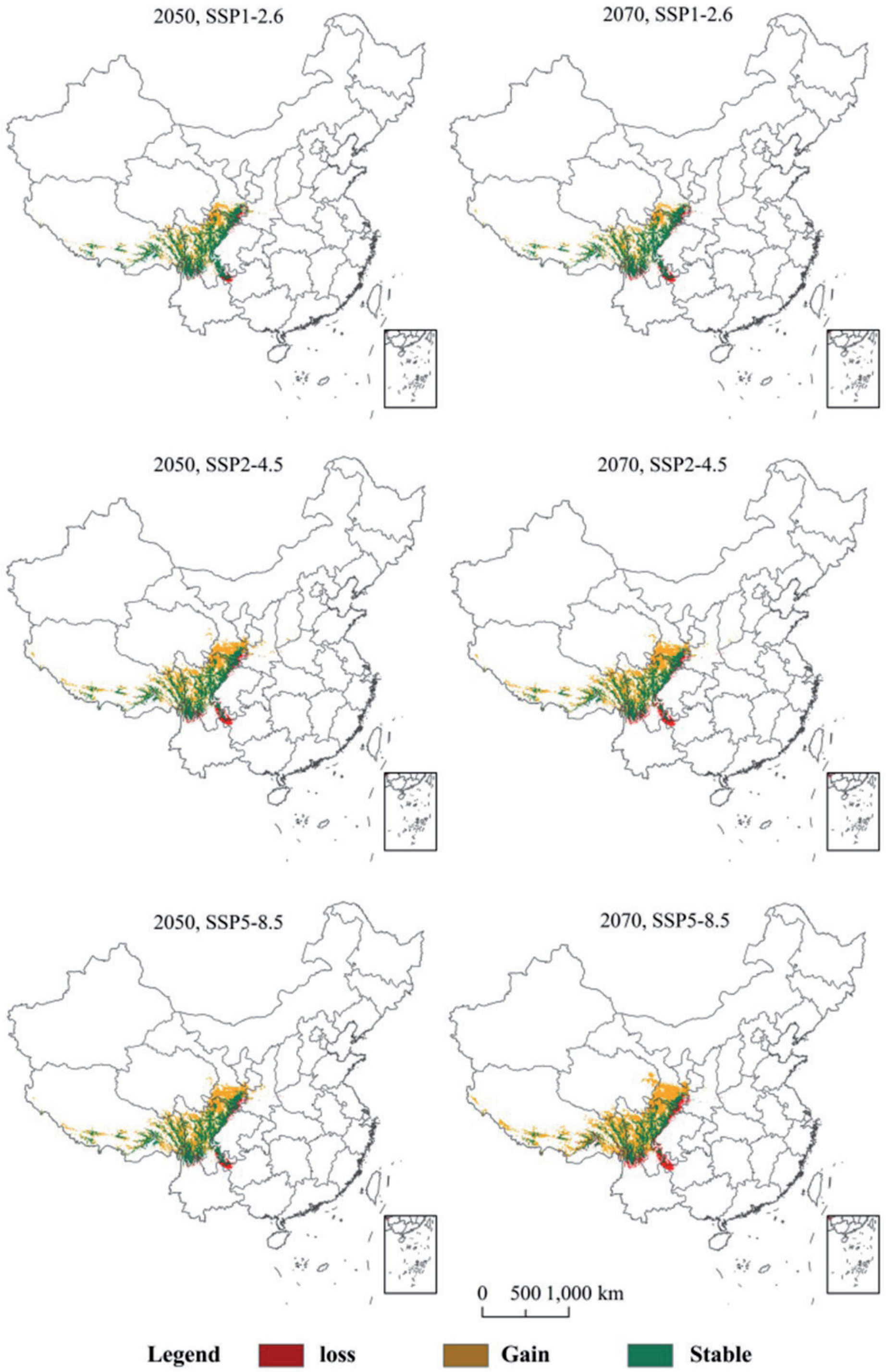

Fig. 4. Changes in the potential geographical distribution of *P. decomposita* under climate change scenarios.

area in a linear pattern, with concentrated distribution in Ganzi, Aba, and Diqing, as well as sporadic or patchy occurrences in Liangshan, Shaotong, Longnan, and Changdu regions, constituting more than half of the total suitable habitat area (Fig. 3, 4 and 5a).

Based on field surveys, literature reviews, and analysis of plant specimen databases, it is evident that *P. decomposita* is primarily distributed in Jinchuan County, Barkam City, Kangding City, and other areas. These regions are all within the predicted suitable zones for this study, which further confirms the reliability of the predictions for *P. decomposita*. The research conducted by Hong et al. [26] indicates the presence of *P. decomposita* in Jinchuan County, Danba County, Barkam City, and Kangding City, while Tan et al. [27] have found its distribution in Li County and Xiaojin County. Notably, all these findings align with the predicted suitable zones, providing further evidence of the accuracy of the predictions.

Overall, the area of highly and moderately suitable habitats for *P. decomposita* in the territory of Ganzi and Aba Prefectures was distributed in a narrow line, which

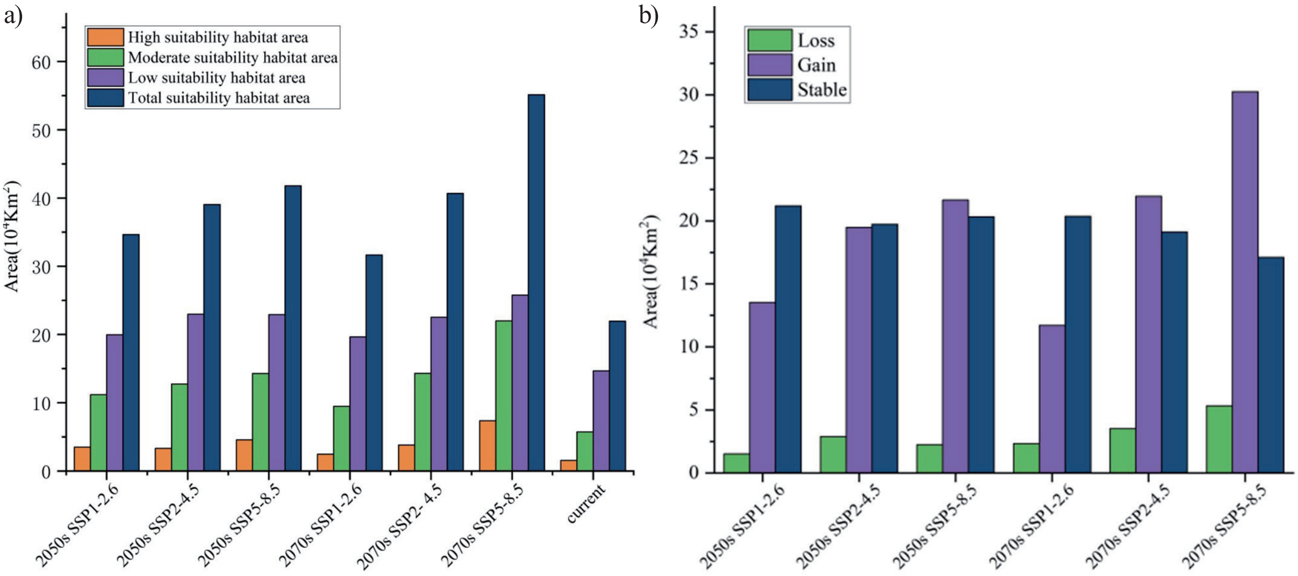

Fig. 5. a) Suitable areas for *P. decomposita* under different climate change scenarios. b) Future changes in suitable habitat area of *P. decomposita* under climate change scenarios.

corresponded well with the actual distribution. This further confirms the accuracy of the simulation results of this study. The extremely narrow range of highly suitable areas also indicates the fundamental reason why *P. decomposita* is an endangered plant species.

Impacts of Future Climate Change on the Geographical Distribution of *P. Decomposita*

In this study, the Maxent model was utilized to predict the potentially suitable habitats of *P. decomposita* in two time periods (2050s and 2070s) under three different emission scenarios (SSP1-2.6, SSP2-4.5, and SSP5-8.5). As a result, the different levels of potentially suitable habitat areas for *P. decomposita* under various climate change backgrounds (Fig. 5a) and the potentially suitable habitats of *P. decomposita* under different climate change scenarios (Fig. 3) were obtained. In all three SSPs (SSP1-2.6, SSP2-4.5, and SSP5-8.5) scenarios, the areas of *P. decomposita*'s suitable habitats showed a significant increase in both the 2050s and 2070s. However, the high suitability zone and moderately suitability zone exhibited a more pronounced increase during these periods. In the 2070s, under the SSP5-8.5 scenario, the high suitability zone increased by 373.08%, which is more than four times its current size. Similarly, the moderate suitability zone also experienced the greatest increase in the 2070s under the SSP5-8.5 scenario, with an enlargement of 282.61%, which is more than three times its current size. These findings indicate that climate change has a substantial impact on the high and moderate suitability zones of *P. decomposita*. Moreover, the total suitable habitat area of *P. decomposita* exhibited a considerable increase in the 2050s and 2070s, with the emergence of numerous new suitable habitats (Fig. 3 and 5a). Compared to the current distribution, in the 2050s, the total suitable habitat area is projected to increase by 57.72%, 77.79%, and 90.26% under the three SSPs (SSP1-2.6, SSP2-4.5, and SSP5-8.5) scenarios, respectively. The high suitability zone is expected to increase by 124.36%, 112.82%, and 193.59%, while the moderate suitability zone is projected to increase by 94.43%, 121.74%, and 148.70%. The low suitability zone is anticipated to expand by 36.22%, 56.82%, and 56.34% (Fig. 5a). Similarly, in the 2070s, compared to the current distribution, the total suitable habitat area is forecasted to increase by 44.11%, 85.23%, and 150.98% under the three SSPs (SSP1-2.6, SSP2-4.5, and SSP5-8.5) scenarios, respectively. The high suitability zone is expected to increase by 59.62%, 145.51%, and 373.08%, while the moderate suitability zone is projected to increase by 65.22%, 149.04%, and 282.61%. The low suitability zone is anticipated to expand by 34.17%, 53.75%, and 75.72% (Fig. 5a). In summary, the future projections indicate a substantial overall increase in the various levels of suitable habitat areas for *P. decomposita*, with the high suitability zone and moderate suitability zone showing clear upward trends. These findings highlight the significant influence of climate change on *P. decomposita*.

Fig. 6 illustrates the trajectory of the centroid movement in the high suitability zone of *P. decomposita* under different periods and climate change scenarios. By analyzing the changes in the area of the high suitability zone and the displacement of its centroid, it is evident that from the reference climate to the 2050s and further to the 2070s, the centroid of the high suitability zone for *P. decomposita* migrates towards different latitudes and directions under the three emission scenarios (Fig. 6). Specifically, under the high emission scenario, the centroid of the high suitability zone shifts towards lower latitudes and the

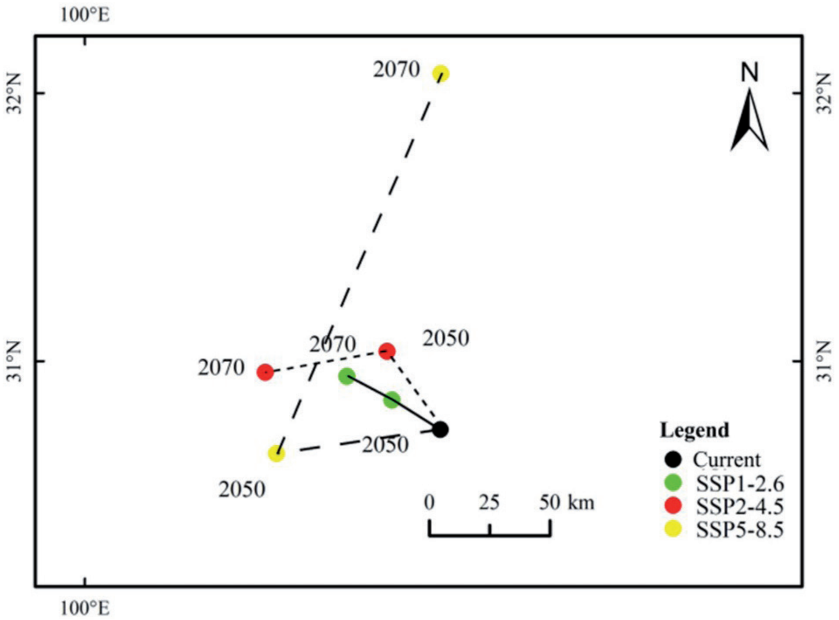

Fig. 6. Variations of the centroids of highly suitable areas of *P. decomposita* under climate change scenarios.

southwest direction, and then towards higher latitudes and the northeast direction, with a relatively significant magnitude of migration. Under the moderate emission scenario, it initially moves towards higher latitudes and a northwest direction, and then towards lower latitudes and a southwest direction. Under the low emission scenario, the centroid consistently moves towards higher latitudes and a northwest direction. In general, under the moderate and low emission scenarios, the centroid of the high suitability zone for *P. decomposita* tends to migrate towards higher latitudes and a northwest direction, with relatively smaller magnitudes of migration. Overall, in the high-emission scenario, the migration magnitude is larger, while in the moderate and low-emission scenarios, the migration magnitude is smaller. Thus, the increase in the size of the high suitability area is most pronounced in the context of high emissions.

Based on the prediction results, the potential geographic distribution of *P. decomposita* is projected to increase at all levels of suitable habitats in both periods, regardless of emission concentration scenarios. In the 2050s and 2070s under high emission scenarios, the high suitability zone of *P. decomposita* exhibits a significant increase with magnitudes of 193.59% and 373.08%, respectively. The moderate suitability zone also experiences substantial growth with magnitudes of 148.70% and 282.61% (Fig. 4 and 5b). This could be attributed to the fact that in areas under high emission scenarios, temperature and precipitation reach ranges suitable for the growth of *P. decomposita*, combined with appropriate elevation and changes in climatic conditions, thereby increasing the survival probability in these regions. Research by Xia et al. [28] also suggests that soil moisture content is an important environmental factor influencing the distribution pattern of *P. decomposita*. Furthermore, studies conducted by Tan et al. [27] indicate that temperature and precipitation have a significant impact on the growth conditions of *P. decomposita*. The centroid of the high suitability zone for *P. decomposita* migrates towards different latitudes and directions under the three emission scenarios; overall, the migration magnitude is larger under high emission scenarios, while it is smaller under moderate and low emission scenarios. Thus, the increase in the area of the high suitability zone is most pronounced in high emission backgrounds (Fig. 6). These findings suggest that in the future, there will be many regions that meet the growth conditions of *P. decomposita*, becoming suitable for its growth and distribution. At the same time, certain regions will no longer be suitable for its growth and distribution. However, the number of newly added suitable habitats will exceed those disappearing. Thomas et al. [29] found that under a warming climate, some species may become extinct, but many others will experience varying degrees of growth and distribution. This indicates that climate warming has both positive and negative effects on the growth and distribution of species. *P. decomposita* has thrived in terms of growth and distribution under a warming climate.

In the 2050s, under the moderate emission scenario, *P. decomposita* experiences the largest loss of suitable habitat area, reaching 2.90×10^4 km^2. Meanwhile, under the high emission scenario, the largest increase in suitable habitat area is observed, amounting to 21.66×10^4 km^2. In the 2070s, under the high emission scenario, both the loss and addition of suitable habitat areas for *P. decomposita* are substantial, measuring 5.34×10^4 km^2 and 30.25×110^4 km^2, respectively (Fig. 5b). Despite the increasing trend of suitable habitat areas for

P. decomposita under future climate change scenarios, the total area remains relatively small for this critically endangered plant species. Therefore, conservation efforts must be prioritized in policy-making and agricultural production. Under the low emission scenario, in the 2050s, the loss of suitable habitat for *P. decomposita* mainly occurs in the western border areas of Guizhou and the southern region of Gannan. Additionally, scattered patches of newly suitable habitats emerged in the western part of Sichuan, northwestern Sichuan, southeastern Tibet, and Gannan (Fig. 4). Comparatively, in the 2070s, there was an expansion of the lost habitat areas, with new losses occurring in the northern border region of Yunnan. The range of newly suitable habitats becomes slightly smaller (Fig. 4). Under the moderate emission scenario, in the 2050s, the loss of suitable habitat for *P. decomposita* is concentrated in the western border areas of Guizhou, the northern border areas of Yunnan, and the southern region of Gannan. Conversely, new suitable habitats develop in the western part of Sichuan, northwestern Sichuan, southeastern Tibet, and Gannan (Fig. 4). In the 2070s, similar to the 2050s, there is an expansion of lost habitat areas, accompanied by an enlargement of newly suitable habitats (Fig. 4). Under the high emission scenario, in the 2050s, the loss of suitable habitat for *P. decomposita* primarily occurs in the western border areas of Guizhou, the northern border areas of Yunnan, and the southern region of Gannan. Meanwhile, new suitable habitats emerged in the western part of Sichuan, northwestern Sichuan, southeastern Tibet, southern Ningxia, and Gannan (Fig. 4). Comparatively, in the 2070s, there was a significant increase in the area of lost habitats and newly suitable habitats (Fig. 4). The potential disappearance of certain regions in *P. decomposita*'s suitable habitats suggests the emergence of new regions where its growth conditions are met. Additionally, the number of newly suitable habitats exceeds the number of disappearing ones, indicating a minimal risk of extinction for *P. decomposita* under natural circumstances. However, precautions must be taken to prevent extensive harvesting, as these critically endangered plant species face immediate extinction risks due to excessive extraction. Research by Feng et al. [17] also demonstrates the significant impact of temperature changes on the survival and distribution of *P. decomposita*. Tan et al. [27] further highlight the substantial influence of temperature and precipitation on the growth conditions of *P. decomposita*. These findings indicate that *P. decomposita* exhibits a strong response to climate change and will migrate towards regions suitable for its growth and distribution.

Climate change indirectly affects the population and distribution characteristics of *P. decomposita* by directly impacting the ecosystem. In addition to the significant influence of climate change on the potential geographic distribution of *P. decomposita*, unsustainable human activities have led to a sharp decline in the wild population of *P. decomposita*. This study only considered environmental variables for the years 2050 and 2070. Therefore, future research on the response of species' potential geographic distributions to climate change can include multiple periods to obtain a comprehensive understanding of the overall trends in the potential geographic distribution of the study subject.

Constraints of Environmental Variables on the Potential Geographic Distribution of *P. Decomposita*

Currently, there is a lack of consensus among researchers regarding the determination of the number of dominant factors. The majority of researchers choose to identify dominant factors based on their contribution rates. However, the selection criteria for determining the degree of dominance are subjective, leading to different standards. In this study, the four environmental factors with the highest contribution rates were selected as the dominant environmental factors. Through analysis and calculations, it was found that altitude, mean temperature of the coldest quarter (Bio11), annual precipitation (Bio12), and temperature seasonality standard deviation (Bio4) accounted for contribution rates of 32.50%, 25.40%, 23.00%, and 11.40%, respectively. The cumulative contribution rate of these four factors reached 92.30%, making them the dominant environmental factors chosen (Table 4).

The examination conducted through the Jackknife method reveals that, when using individual environmental factor variables, temperature seasonality standard deviation (Bio4), mean temperature of the coldest quarter (Bio11), annual precipitation (Bio12), and altitude (Altitude) have the greatest impact on the normalized training gain for *P. decomposita*. This indicates that these environmental factor variables play a dominant role in constraining the growth of *P. decomposita* (Fig. 7).

The response curves of species' survival probabilities to environmental factors in the MaxEnt model output are commonly used to assess the relationship between species occurrence probability and environmental factors (Fig. 8). When the probability of *P. decomposita*'s occurrence exceeds the threshold for high suitability habitats, the corresponding range of environmental factors represents the suitable range for the survival of *P. decomposita*.

The results from the MaxEnt model reveal that when the mean temperature of the coldest quarter (Bio11) reaches -4.27ºC, the survival probability of *P. decomposita* reaches the threshold for high-suitability habitats. At a mean temperature of the coldest quarter (Bio11) of 0.46ºC, the occurrence probability of *P. decomposita* peaks, after which the survival probability decreases as the mean temperature of the coldest quarter (Bio11) increases. When the mean temperature of the coldest quarter (Bio11) reaches 5.2ºC, the survival probability of *P. decomposita*

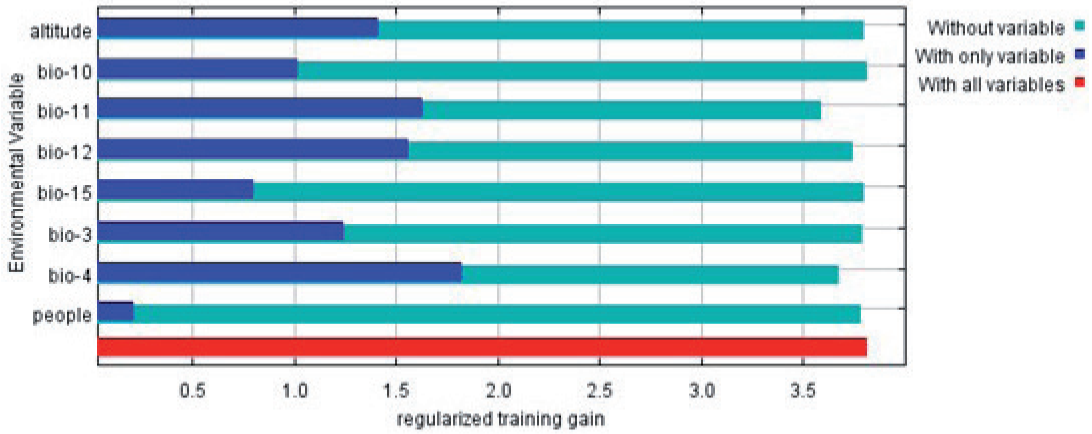

Fig. 7. The jackknife test result of environmental factor for *P. decomposita*.

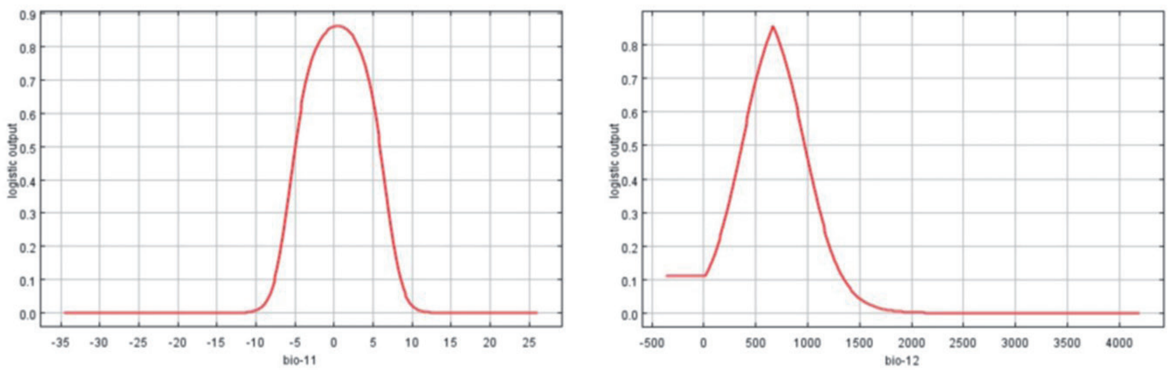

Fig. 8. Response curves of existence probality of *P. decomposita*.

decreases to 0.6. Therefore, the suitable range of the mean temperature of the coldest quarter (Bio11) for *P. decomposita*'s survival is -4.27 to 5.2ºC. When the annual precipitation (Bio12) is 434.8 mm, the survival probability of *P. decomposita* reaches the threshold for high-suitability habitats. As the annual precipitation increases, the survival probability of *P. decomposita* shows an upward trend, peaking at an annual precipitation (Bio12) of 663.0mm. With a further increase in annual precipitation (Bio12), the survival probability of *P. decomposita* starts to decline, reaching 0.6 at annual precipitation (Bio12) of 900.3 mm. Hence, the suitable range of annual precipitation (Bio12) for *P. decomposita*'s survival is 434.8 to 900.3 mm. In conclusion, as the dominant environmental factors influencing the survival of *P. decomposita*, namely annual precipitation (Bio12) and the mean temperature of the coldest quarter (Bio11), increase, the survival probability of *P. decomposita* initially rises and then declines. The narrow range of suitable conditions indicates its high requirements for temperature and precipitation levels.

Climate factors are critical in determining the potential distribution of species at a macroscale and studying the interaction between plants and climate is an important aspect of ecology. The results from the MaxEnt model indicate that altitude, temperature seasonality standard deviation (Bio4), mean temperature of the coldest quarter (Bio11), and annual precipitation (Bio12) are the dominant environmental factors constraining the potential geographic distribution of *P. decomposita* (Table 1). This study highlights the significance of altitude as a key factor limiting the potential geographic distribution of *P. decomposita*. To some extent, the probability of *P. decomposita*'s occurrence increases with higher altitudes. Based on specimen records, *P. decomposita* is primarily distributed in the provinces of Sichuan, Gannan, and Aba, where its growth is constrained by altitude. In low-altitude areas, it struggles to grow and reproduce, indicating that regions with excessively low altitudes are unsuitable for its normal development. This finding aligns with the research conducted by Zhou et al. [28], confirming that altitude has the most prominent effect on the growth and reproduction of *P. decomposita*. Xia et al. [30] also demonstrated the significance of altitude as one of the crucial environmental factors affecting the distribution pattern of *P. decomposita*. Regarding temperature seasonality standard deviation, it also influences the probability of *P. decomposita*'s occurrence. As the seasonal temperature variation in regions suitable for *P. decomposita*'s natural distribution increases, the probability of its occurrence also rises. However, when the variation becomes too extreme or falls below a certain threshold, it exceeds the suitable range for *P. decomposita*'s survival. Therefore, regions with a high probability of *P. decomposita*'s occurrence exhibit noticeable temperature seasonality, but the variations should not be excessively drastic. Feng et al. [17] similarly demonstrated the significant impact of temperature seasonality standard deviation on the probability of *P. decomposita*'s occurrence. The mean temperature of the coldest quarter also restricts the distribution of *P. decomposita* to a considerable extent. With an increase in the mean temperature of the coldest quarter, the probability of *P. decomposita*'s occurrence gradually rises. However, as the mean temperature continues to rise, the probability declines. Similarly, annual precipitation moderately constrains the distribution of *P. decomposita*. As annual precipitation increases, the probability of *P. decomposita*'s occurrence gradually rises. However, with a sustained increase in annual precipitation, the probability decreases. These findings indicate that both temperature and precipitation have substantial influences on the distribution of *P. decomposita*. Wu et al. [31] found that *P. decomposita* has a higher probability of occurrence in areas with higher soil moisture. Xia et al. [30] emphasized the importance of soil moisture content as a significant environmental factor limiting the distribution pattern of *P. decomposita*, while Tan et al. [27] highlighted the substantial influence of temperature and precipitation on the growth conditions of *P. decomposita*. These studies provide further support for the accuracy of the results obtained in this research.

Conservation Strategies for *P. Decomposita*

Climate change has potentially accelerated species extinctions, reduced species diversity, and made regional ecosystems more vulnerable. However, some species may develop new physiological traits to adapt to climate change [32, 33]. Relevant studies indicate that changes in the spatial and temporal patterns of climate can alter the geographical distribution patterns of plants, posing a threat to their natural habitats [3, 34, 35]. To mitigate the impact of climate change on ecosystems, modeling species distributions can effectively inform conservation strategies. Based on the current growth status and predicted potential distribution of *P. decomposita*, the following recommendations are proposed for its protection and utilization:

(1) Enhancement of *P. decomposita* seedling trials to promote population renewal. The limited number of wild *P. decomposita* seedlings is one of the key reasons for its endangerment. Research on seed germination and seedling production can improve the age structure of *P. decomposita* populations, promote population renewal, and replenish population size.

(2) Reduce anthropogenic interference and protect wild *P. decomposita* communities. *P. decomposita* has a low resistance to external disturbances and is sensitive to environmental changes. Since *P. decomposita* inhabits the riverbanks of the Dadu River and Min River in the upstream basin, which are hotspots for hydropower development, the construction of hydroelectric stations or reservoirs can directly or indirectly alter the habitat conditions of *P. decomposita*, which may lead to a decrease in its population. Therefore, the impact of the construction project on the ecological environment of the *P. decomposita* habitat should be carefully considered before the project is implemented. Appropriate and effective conservation measures should be taken in advance to avoid irreversible consequences for *P. decomposita*.

(3) When releasing *P. decomposita* into the wild or implementing translocation conservation, the results of suitable area delineation for *P. decomposita* can serve as a scientific reference for site selection. If the habitat conditions for *P. decomposita* have been severely disrupted and on-site conservation is no longer feasible, measures such as translocation conservation should be taken. During translocation or wild release, efforts should be made to select sites within the most suitable areas for *P. decomposita*.

(4) Strengthen publicity and education for *P. decomposita* conservation. As an endemic plant species in China, *P. decomposita* represents a valuable natural asset. Local governments should recognize its significance as a valuable resource and utilize it responsibly to create economic benefits and promote poverty alleviation. At the same time, efforts should be intensified to protect *P. decomposita*, preventing further decline of the population due to unauthorized collection and illegal harvesting.

(5) To promote the cultivation of *P. decomposita*. Given its medicinal, oleaginous, and ornamental value, the promotion of the cultivation of *P. decomposita* is necessary. The results of ecological and geological suitability assessments should be taken into account when selecting planting sites for *P. decomposita* to ensure that appropriate sites are selected.

Conclusions

In this study, the dominant environmental factors affecting the geographic distribution of *P. decomposita* were altitude, mean temperature of the coldest quarter, annual precipitation, and seasonal variation of temperature, with standard deviation contributions of 32.50%, 25.40%, 23.00%, and 11.40%, respectively, and the cumulative value of the four amounted to 92.30%. Currently, the suitable area of *P. decomposita* is mainly located in Sichuan Province in a strip-like distribution, and its high suitable area is mainly distributed in Ganzi and Aba Prefectures in a thin strip-like distribution, with an area of 1.56×10^4 km^2, accounting for 7.10% of the total suitable area. Under future climate change scenarios, the total suitable area of *P. decomposita* showed an increasing trend, and the highly suitable area increased more obviously. Under the three emission scenarios, the center of mass of *P. decomposita*'s high habitability zone migrated in different latitudes and directions, with the greatest migration under the high concentration scenario. By analyzing the current potential distribution of *P. decomposita* and combining it with field surveys, it was found that *P. decomposita* suffers from population isolation and low population size and that appropriate conservation measures must be taken to protect *P. decomposita*.

Author Contributions

M.L., M-M.S. planned and supervised the project.P-S.Q., W.G., D-C.C. L-Hperformed the experiments, analyzed the data, contributed reagents/materials/analysis tools. K.C., H-W.W., D-Z.D. contributed to data collection and evaluation. Y.H. revised the manuscript.

Funding

This work was funded by the Sichuan,Science,and, Technology,Program（2023ZYD0102）,the,Scientific,Research,Initiation,Project,of,Mianyang,Normal,University,(QD2021A37,,QD2023A01)，the Foundation of Key Laboratory of Southwest China Wildlife Resources Conservation(Ministry of Education) (XNYB22-05), the open project from the Ecological Security and Protection Key Laboratory of Sichuan Province (ESP1703).

Conflict of Interest

The authors declare no competing interests.

References

1. SHEN T., YU H., WANG Y.Z. Assessing the impacts of climate change and habitat suitability on the distribution and quality of medicinal plant using multiple information integration: Take Gentiana rigescens as an example. Ecological Indicators, **123**, **2021**.
2. RU L., CHEN J., JIANG P., CHEN R., LIN H., LI Z., XUE Q., LIU C., HUANG Y. Simulation of Potential Suitable Distribution of Endangered Medicinal of *Paeonia rockii* under Climate Change Scenarios. Polish Journal of Environmental Studies, **32** (3), 3534, **2023**.
3. HUANG Y., ZENG Y., JIANG P., CHEN H., YANG J.T. Prediction of potential geographic distribution of endangered and relict tree species *Dipteronia sinensis* in China based on MaxEnt and GIS. Polish Journal of Environmental Studies, **31** (4), 3597, **2022**.
4. YANG J.T., HUANG Y., JIANG X., CHEN H., LIU, M., WANG R. Potential geographical distribution of the edangred plant *Isoetes* under human activities using MaxEnt and GARP. Global Ecology and Conservation, **38**, e02186, **2022**.
5. LI Y.Q., KONG D.X., FU Y., SUSSMAN M.R., WU H. The effect of developmental and environmental factors on secondary metabolites in medicinal plants. Plant Physiology and Biochemistry, **148**, 80, **2020**.
6. LIU L., ZHANG Y.Y., HUANG Y., ZHANG J.D., MOU Q.Y., WANG R.L., LI Y.J., ZHANG D.Q. Simulation of potential suitable distribution of original species of *Fritillariae Cirrhosae Bulbus* in China under climate change scenarios. Environmental Science and Pollution Research, **29** (15), 22237, **2022**.
7. LIU L., GUAN L.L., ZHAO H,X., HUANG Y, MOU Q.Y., LIU K, CHEN T.T., WANG X.Y., ZHANG Y., WEI B., HU J.Y. Modeling habitat suitability of *Houttuynia cordata* Thunb (Ceercao) using MaxEnt under climate change in China, Ecological Informatics, **63**, **2021**.
8. HUANG X.M, ZHAO C., CAI K., HUANG Y. Climatic changes in the Anthropocene have increased the suitable habitat areas of *Paeonia delavayi* in China. Polish Journal of Environmental Studies, **32** (5), 1, **2023**.
9. PHILLIPS S.J., ANDERSON R.P., SCHAPIRE R.E. Maximum entropy modeling of species geographic distributions. Ecological Modelling, **190** (3-4), 231, **2006**.
10. YANG J.T., JIANG X., CHEN H., JIANG P., LIU M., HUANG Y. Predicting the Potential Distribution of the Endangered Plant *Magnolia wilsonii* Using MaxEnt under Climate Change in China. Polish Journal of Environmental Studies, **31** (5), 4435, **2022**.
11. XIANG L., WANG H., LIU L., ZHAO H., HUANG Y., CHEN H., MA Y., MAO Y., HU L., HU J. Distribution and Protection of Chinese *Beech* under the Background of Climate Change. Polish Journal of Environmental Studies, **31** (3), 2341, **2022**.
12. YANG J., JIANG P., HUANG Y., YANG Y., WANG R., YANG Y. Potential geographic distribution of relict plant *Pteroceltis tatarinowii* in China under climate change scenarios. Public Library of Science, **17** (4), e0266133, **2022**.
13. National Forestry and Grassland Administration, Ministry of Agriculture and Rural Affairs. List of National Key Protected Wild Plants. [EB/OL]. http://www.forestry.gov.cn/main/3954/20210908/163949170374051.html, [In Chinese].
14. Institute of Zoology, Chinese Academy of Sciences. the Convention on International Trade in Endangered Species of Wild Fauna and Flora. [EB/OL]. http://www.cites.org.cn/citesgy/fl/201911/t20191111_524091.html, [In Chinese].
15. Ministry of Environmental Protection and Chinese Academy of Sciences. Red List of Biodiversity in China - Higher Plants Volume. [EB/OL]. https://www.mee.gov.cn/gkml/hbb/bgg/201309/t20130912_260061.htm, [In Chinese].
16. LONG Z.L., YANG L.X., YANG R., LANG B.Y., WANG J. Medicinal ethnobotany research on *Paeonia* sect. Moutan through textual evidence. Guihaia, **41** (02), 308, **2021** [In Chinese].
17. FENG Y. Study on the Influence of Eco-geological Environment on the Distribution of *Paeonia szechuanica*. Chengdu University of Technology, **2019** [In Chinese].
18. RUSHING C.S., RUBENSTEIN M., LYONS J.E., RUNGE M. Using value of information to prioritize research needs for migratory bird management under climate change: a case study using federal land acquisition in the United States. Biological Reviews, **95** (04), **2020**.
19. BROOKS T.M., MITTERMEIER R.A., DA F.G., GERLACH J., HOFFMANN M., LAMOREUX J.F.,

MITTERMEIER C.G., PILGRIM J.D. Global biodiversity conservation priorities. Science, **313** (5783), 58, **2006**.

20. DONG X., ZHANG J., GU X., WANG Y.J., BAI W.K., HUANG Q.Y. Evaluating habitat suitability and potential dispersal corridors across the distribution landscape of the Chinese red panda (*Ailurus styani*) in Sichuan, China[J]. Global Ecology and Conservation, **28** (09), e01705, **2021**.
21. VERONIKA E., SANDRINE B., MEEHL G.A., SENIOR C.A., BJORN S., STOUFFER R.J., TAYLOR K.E., Overview of the coupled model intercomparison project phase 6 (CMIP6) experimental design and organization. Geoscientific Model Development, **9** (05), 1937, **2016**.
22. XIAN X.Q., ZHAO H.X., WANG R., HUANG H.K., CHEN B.X., ZHANG G.F., LIU W.X., WAN F.H. Climate change has increased the global threats posed by three ragweeds (*Ambrosia* L.) in the Anthropocene. Science of the Total Environment, 160252, **2023**.
23. ZHAO H.X., XIAN X.Q., YANG N.W., ZHANG Y.J., LIU H., WAN F.H., GUO J.Y., LIU W.X. Insights from the biogeographic approach for biocontrol of invasive alien pests: Estimating the ecological niche overlap of three egg parasitoids against *Spodoptera frugiperda* in China. Science of the Total Environment, 160785, **2023**.
24. WANG R.L., JIANG C.X., GUO X., CHEN D.D., YOU C., ZHANG Y., WANG M.T., LI Q. Potential distribution of *Spodoptera frugiperda* (JE Smith) in China and the major factors influencing distribution. Global Ecology and Conservation, **21**, e00865, **2020**.
25. WANG R., YANG H., LUO W., WANG M., LI Q. Predicting the potential distribution of the Asian citrus psyllid, *Diaphorina citri* (Kuwayama), in China using the Maxent model. PeerJ, **7**, e7323, **2019**.
26. HONG D.Y., ZHOU S.L., HE X.J., YUAN J.H., ZHANG Y.L., CHENG F.Y., ZENG X.L., WANG Y., ZHANG X.X. Current status of wild tree peony species with special reference to conservation. Biodiversity Science, **25** (07), 781, **2017** [In Chinese].
27. TAN L.P., ZENG W.Q., LIU X.A., ZHOU X.H., YANG X., PENG P.H. Differences in functional characters of *Paeonia decomposita* from different provenances and their relationships with environmental factors. Northern Horticulture, (21), 48, **2019** [In Chinese].
28. ZHOU X.H., WANG J., LIU X.A., PENG P.H., MA Z.F., GUO H.Y. Relationship between follicles and seeds traits of *Paeonia decomposita* and environment factors. Journal of Northeast Forestry University, **46** (09), 41, **2018** [In Chinese].
29. CHRIS D.T., ALISON C., RHYS E.G., MICHEL B., LINDA J.B., YVONNE C.C., BAREND F.N., MARINEZ F.S., ALAN G., LEE H., LESLEY H., BRIAN H., ALBERT S.J., GUY F.M., LERA M., MIGUEL A.H., PETERSON A.T., OLIVER L.P., STEPHEN E.W. Extinction risk from climate change. Nature, **427**, 145, **2004**.
30. XIA X.M., WANG J., PENG P.H., LIU X.A. Quantitative classification and ordination of *Paeonia decomposita* habitat communities. Journal of Northeast Forestry University, **45** (01), 37, **2017** [In Chinese].
31. WU H.W., ZHONG J., JIA C., LUO J.X. A study of the distribution characteristics of *Paeonia decomposita* resources in Sichuan. Journal of Sichuan Forestry Science and Technology, **41** (02), 53, **2020** [In Chinese].
32. RUSHING C.S., RUBENSTEIN M., LYONS J.E., RUNGE M.C. Using value of information to prioritize research needs for migratory bird management under climate change: a case study using federal land acquisition in the United States. Biological Reviews, **95** (04), **2020**.
33. GARCIA K., LASCO R., INES A., LYON B., PULHIN F. Predicting geographic distribution and habitat suitability due to climate change of selected threatened forest tree species in the Philippines. Applied Geography, **44**, 12, **2013**.
34. INAGUE G.M., ZWIENER V.P., MAROUES M.C.M. Climate change threatens the woody plant taxonomic and functional diversities of the *Restinga* vegetation in Brazil. Perspectives in Ecology and Conservation, **19** (1), 53, **2021**.
35. GARAH K., BENTOUANI A. Using the MaxEnt model for assessing the impact of climate change on the Aurasian *Aleppo pine* distribution in Algeria. African Journal of Ecology, **57** (4), 500, **2019**.