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Effects of Climate Change on the Spatial Distribution of the Threatened Species *Rhododendron purdomii* in Qinling-Daba Mountains of Central China: Implications for Conservation

Hao Dong [1], Ningning Zhang [2], Simin Shen [1], Shixin Zhu [3], Saibin Fan [1] and Yang Lu [3,4,*]

[1] School of Agricultural Sciences, Zhengzhou University, Zhengzhou 450001, China
[2] Yunnan Key Laboratory for Integrative Conservation of Plant Species with Extremely Small Populations, Kunming Institute of Botany, Chinese Academy of Sciences, Kunming 650201, China
[3] School of Life Sciences, Zhengzhou University, Zhengzhou 450001, China
[4] Funiu Mountains Biological Resources and Ecological Environment Observation and Research Station, Zhengzhou University, Zhengzhou 450001, China
* Correspondence: luyang@zzu.edu.cn

Abstract: The plant species in the mountainous regions might be relatively more vulnerable to climate change. Understanding the potential effects of climate change on keystone species, such as *Rhododendron* species in the subalpine and alpine ecosystems, is critically important for montane ecosystems management and conservation. In this study, we used the maximum entropy (MaxEnt) model, 53 distribution records, and 22 environmental variables to predict the potential impacts of climate change on the distribution of the endemic and vulnerable species *Rhododendron purdomii* in China. The main environmental variables affecting the habitat suitability of *R. purdomii* were altitude, temperature seasonality, annual precipitation, slope, and isothermality. Our results found suitable distribution areas of *R. purdomii* concentrated continuously in the Qinling-Daba Mountains of Central China under different climate scenarios, indicating that these areas could potentially be long-term climate refugia for this species. The suitable distribution areas of *R. purdomii* will expand under the SSP126 (2070s), SSP585 (2050s), and SSP585 (2070s) scenarios, but may be negatively influenced under the SSP126 (2050s) scenario. Moreover, the potential distribution changes of *R. purdomii* showed the pattern of northward shift and west–east migration in response to climate change, and were mainly limited to the marginal areas of species distribution. Finally, conservation strategies, such as habitat protection and assisted migration, are recommended. Our findings will shed light on biotic responses to climate change in the Qinling-Daba Mountains region and provide guidance for the effective conservation of other endangered tree species.

Keywords: *Rhododendron*; climate change; MaxEnt; species distribution; conservation; Qinling-Daba Mountains

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1. Introduction

Mountain ecosystems are hotspots of biodiversity and centers of endemism, with numerous threatened species, and are particularly sensitive to environmental changes [1,2]. Global climate changes pose a great threat to mountain plant species diversity, which significantly impact on plant distribution and phenology, causing reductions in population size and changes in community composition, and even extinction of alpine species and communities [3,4]. It is of key importance to understand the climate change vulnerability and adaptability of mountain plant species. Predicting the ecological effects of climate change on the distribution pattern of species is a matter of primary concern [5,6]. However, our knowledge of how high-elevation plant species' geographic distribution responds to global climate change is still limited [4,7]. Understanding potential effects of climate change on keystone species, such as *Rhododendron* species in the subalpine and alpine ecosystems [8], is critically important for montane ecosystems management and conservation.

Rhododendron (Ericaceae) is a species-rich genus with more than 1000 species globally [9]. It is the largest genus of woody plants in the Northern Hemisphere, including many horticulturally valuable species. There are about 571 *Rhododendron* species in China, and many species are endemic and threatened [10,11]. As a keystone element of montane ecosystems, many *Rhododendron* species represent the dominant or constructive elements in the subalpine and alpine plant communities. They play a vital role in delivering ecosystem services of slope stabilization and watershed protection, as well as in supporting biodiversity [8]. Therefore, *Rhododendron* has been suggested as an ideal system for ecological and evolutionary studies [11–13]. In the past, most related studies on *Rhododendron* species have focused on the Himalaya–Hengduan Mountains, which is a center of diversity and diversification in the genus [5,12–14]. The Qinling-Daba Mountains region (QBM) of central China is also referred to as one of the biodiversity hotspots for *Rhododendron* in China [15]. However, few studies have been undertaken concerning the ecology and conservation of *Rhododendron* species restricted to this region.

The QBM has been recognized as a biodiversity hotspot of Chinese endemic plant species [16]. Additionally, the QBM sits in the transitional zone from the subtropical to the warm temperate zone of China, and is also the natural boundary between northern and southern China [17]. Thus, the regional vegetation exhibits a high degree of complexity, and transitional and climatic sensitivity [18]. As a landmark vegetation type in this area, evergreen vegetation dynamics and responses to climate change are important for ecosystem conservation and management [17,19]. Previous studies of the effects of climate change on species distribution patterns to date have concentrated on evergreen coniferous species, such as *Pinus bungeana*, *Pinus tabuliformis*, and *Pinus massoniana*, with little attention paid to evergreen broadleaved woody plants in the QBM [20,21]. Therefore, the study of climate change driven impact on the representative species, such as evergreen broad-leaved *Rhododendron* spp. in high-altitude habitats, is important for gaining insights into the vulnerability of the biodiversity in response to climate change and related conservation strategies in the QBM.

Rhododendron purdomii Rehder & E. H. Wilson is an evergreen shrub or small tree species within the genus *Rhododendron*. This species is endemic to the QBM and occurs in small and isolated populations scattered at the top of island-like mountains (sky islands) in Henan, Shaanxi, and Gansu provinces [22,23]. It was discovered by William Purdom in 1910 on the Taibai Mountain of Shaanxi province, and was named for the plant collector [10]. The montane forests containing *R. purdomii* as one of the dominants mainly occur at 1800–3500 m altitude. In these areas, *R. purdomii* often grows with other species, including *Pinus*, *Abies*, *Quercus*, *Acer*, *Betula*, and *Fargesia*, and plays a vital role in soil conservation and erosion control [24]. Furthermore, it is a valuable ornamental plant with fascinating flowers, and used as a traditional Chinese medicinal plant. It attracts many visitors during the flowering stage. Thus, this species has been subject to some level of habitat destruction and human disturbance [23,25]. *R. purdomii* has been classified as Vulnerable (VU) in the Threatened Species List of China's Higher Plants [26]. Threatened species with small population size and sky island distribution are likely to be sensitive to environmental and climatic changes [22]. Therefore, understanding the spatial distribution pattern and range shifts are required to effectively conserve and restore this species. However, the impact of climate change on *R. purdomii* has not been studied at the species level.

The maximum entropy (MaxEnt) model is an effective tool for predicting range shifts of species under climate change. To date, several studies based on MaxEnt have demonstrated that the effects of climate change on the distribution of *Rhododendron* species are complex and species-specific [6,14,27,28]. Here, we use the MaxEnt model to examine the potential impacts of climate change on the distribution of *R. purdomii* in the QBM. We aimed to: (a) explore the potential distribution range of *R. purdomii* under climate change, and (b) identify the key environmental factors that affect *R. purdomii* spatial distribution. This study will shed light on biotic responses to climate change in the QBM region and provide guidance for effective management and conservation of this vulnerable species.

2. Materials and Methods

2.1. Occurrence Data and Study Area

Occurrence data of *R. purdomii* were obtained from the Chinese Virtual Herbarium (http://www.cvh.ac.cn/, accessed on 1 July 2022), the published studies [23,24,29], and our field survey. All specimens and locations were carefully verified according to the Flora of China [10], the experience of authors, and field observations. We removed unclear or repeated records, as well as specimen records with erroneous identification. In order to avoid sampling bias and reduce spatial autocorrelation, only one point was retained in a 2.5 arc-minute resolution grid cell. In total, 53 effective localities of *R. purdomii* were used in distribution modeling (Figure 1).

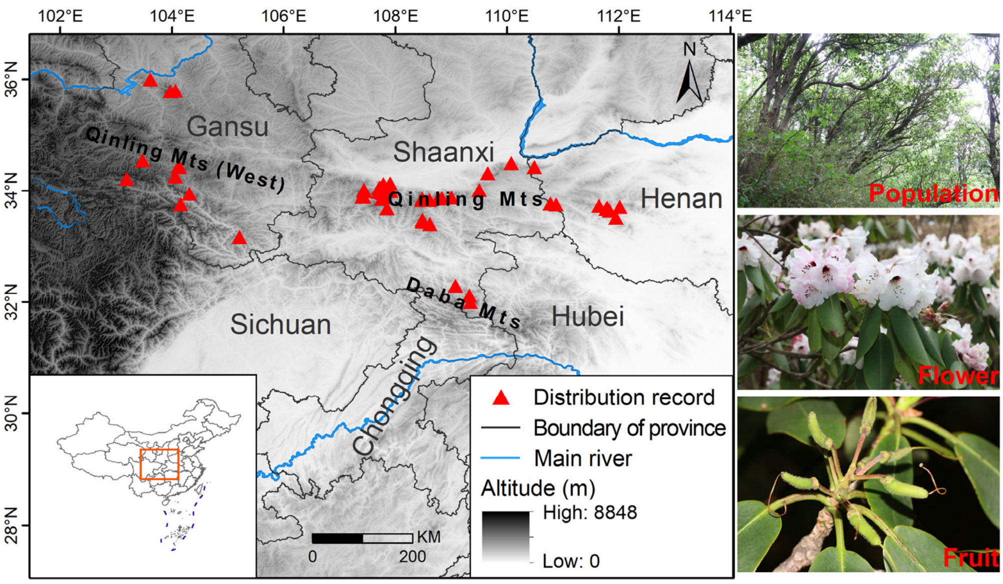

Figure 1. Occurrence points of *Rhododendron purdomii* across the Qinling-Daba Mountains.

According to the collected occurrence data, *R. purdomii* is mainly found between 103°–112° E and 32°–36° N in the Qinling-Daba Mountains of Central China (Figure 1). An area with an extent of 101°–114° E and 30°–38° N was used accordingly in this study.

2.2. Environmental Variables Selection

A total of 22 environmental variables were used in this study, including 19 bioclimatic variables (Bio01-Bio19) related to temperature and precipitation and 3 topographic variables (altitude, aspect, and slope) (Table 1). The 19 bioclimatic variables (Bio01-Bio19) and altitude data were directly obtained from the WorldClim Database (http://www.worldclim.org, accessed on 1 July 2022) at a resolution of 2.5 arc-min [30,31]. The aspect and slope data were derived from the altitude data in ArcGIS 10.7 (https://www.esri.com/, last accessed on 1 July 2022, Esri, Redlands, CA, USA).

Since a fossil record of *R. purdomii* is lacking, the paleoclimate data, including the Mid-Holocene (ca. 6000 yr BP) and the Last Glacial Maximum (LGM, ca. 22,000 yr BP), were determined based on the Community Climate System Model Version 4 (CCSM4) [32], which was used to simulate the potential geographical distribution of *R. purdomii* in the past. The climate data of the present represent mean values from 1970 to 2000, which could be used to model the current potential suitable distribution area of *R. purdomii*. The future data, including the 2050s (average for 2041–2060) and 2070s (average for 2061–2080), were obtained from BCC-CSM2-MR (Beijing Climate Centre, Beijing, China) model, which has a strong simulation capability for China and has four Shared Socioeconomic Pathways (SSPs) [30]. The SSPs, which included the low emission scenarios of SSP126, the medium emission scenarios of SSP245 and SSP370, and the high emission scenarios of SSP585, were from the sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC) in 2021 [33]. Compared with the scenarios used in previous studies, the SSPs were the newest emissions scenarios driven by different socioeconomic assumptions, and could better describe the global socio-economic development scenario [34]. The lowest and the highest emission scenarios (SSP126 and SSP585) were selected to predict the potential suitable habitat of *R. purdomii* in the 2050s and 2070s.

Table 1. Environmental variables and contribution rate of the variables used in this study.

Variable Type	Variable	Description	Contribution (%)
Temperature	Bio01	Annual mean temperature (°C)	-
	Bio02	Mean diurnal range (°C)	-
	Bio03	**Isothermality (Bio2/Bio7 × 100)**	**22.8**
	Bio04	**Temperature seasonality (standard deviation × 100) (C of V)**	**19.5**
	Bio05	Max temperature of warmest month (°C)	-
	Bio06	Min temperature of coldest month (°C)	-
	Bio07	Temperature annual range (°C)	-
	Bio08	Mean temperature of wettest quarter (°C)	-
	Bio09	Mean temperature of driest quarter (°C)	-
	Bio10	Mean temperature of warmest quarter (°C)	-
	Bio11	Mean temperature of coldest quarter (°C)	-
Precipitation	**Bio12**	**Annual precipitation (mm)**	**13.6**
	Bio13	Precipitation of wettest month (mm)	-
	Bio14	Precipitation of driest month (mm)	-
	Bio15	Precipitation seasonality (C of V)	-
	Bio16	Precipitation of wettest quarter (mm)	-
	Bio17	Precipitation of driest quarter (mm)	-
	Bio18	Precipitation of warmest quarter (mm)	-
	Bio19	Precipitation of coldest quarter (mm)	-
Topography	**ALT**	**Altitude (m)**	**17.7**
	ASP	**Aspect(°)**	**0.9**
	SLP	**Slope(°)**	**25.6**

Note: The six variables in bold were selected for further modeling.

The environmental data from species distribution points were extracted by the R package "raster" (https://cran.r-project.org/web/packages/raster, last accessed on 10 July 2022). To avoid multicollinearity, the 19 bioclimatic variables and 3 topographic variables were filtered through the Pearson's correlation analysis and the contribution for the MaxEnt model. When two environmental variables were highly correlated ($|r| > 0.8$), the variable that had a higher percent contribution to the MaxEnt model was retained. Finally, we retained six environmental variables for subsequent analyses, which were isothermality (Bio03), temperature seasonality (Bio04), annual precipitation (Bio12), altitude (ALT), aspect (ASP), and slope (SLP) (Table 1). In ArcGIS 10.7, the environmental variables were converted into ASCII format.

2.3. Model Optimization and Setting

MaxEnt v3.4.4 (https://biodiversityinformatics.amnh.org/open_source/maxent/, last accessed on 1 July 2022) was used to assess the importance of environmental variables and simulate the potential distribution of *R. purdomii* in different periods [35]. Firstly, MaxEnt software was run with default parameters to evaluate the contribution of all environmental variables to the model, so as to be used for the selection of environmental variables. Then, the model parameters were optimized for more accurate predictions. The regularization multiplier (RM) values were set to 0.5–5.0 with steps of 0.5. The feature classes (FC) included linear (L), hinge (H), product (P), quadratic (Q), and threshold (T). Six FC combinations (L, H, LQ, LQH, LQHP, and LQHPT) were tested in this study [36]. In total, 60 candidate models were evaluated by using the R package "Kuenm" [37]. In this package, the best model was selected based on significance, omission rates ($E \leq 5\%$), and model complexity (AICc) [37,38]. Finally, the optimal FC combination was LQ and the RM value was 0.5.

In this study, 75% of the distribution points of *R. purdomii* were randomly selected for model training and 25% for model testing. Test samples were extracted by the bootstrap method, and the operation was repeated 10 times. The number of background points was 10,000. The bootstrap method was used to test the model performance. The jackknife test was used to assess the relative importance of each variable [35]. The area under the curve (AUC) of the receiver operating characteristic (ROC) approach was used to assess the model accuracy [39]. The AUC value was divided into five grades: fail (0.5–0.6), poor (0.6–0.7), fair (0.7–0.8), good (0.8–0.9), and excellent (0.9–1.0) [40]. In addition, we also used the R package "Kuenm" to calculate AUC ratios in order to estimate the predictive performance of the model [37]. The model accuracy can be considered as excellent when the AUC ratios values are greater than 1.8 or close to 2 [36].

2.4. Geospatial Analyses

The model prediction was a 0–1 continuous probability layer, which can be used to determine the growth suitability of plants in various environments, and to study ecological suitability zoning. The potential distribution area and the area of different suitable areas in each period were calculated by ArcGIS. In ArcGIS software, according to the average of 10 replicates of the MaxEnt model, the potential distribution of *R. purdomii* were divided into four grades using the "reclass" function, including unsuitable (0–0.2), low suitability (0.2–0.4), medium suitability (0.4–0.6), and high suitability (0.6–1) [41]. The SDM toolbox in ArcGIS was used to calculate the change of potential distribution area in the different periods [42]. The area change range of the potential distribution areas in each period was calculated by the "distribution changes between binary SDMs" tool. Moreover, the R package "ConR" was used to calculate the extent of occurrence (EOO) and area of occupancy (AOO) of *R. purdomii* based on the effective occurrence data [43].

3. Results

3.1. Model Performance and Key Environmental Variables

The potential distribution of *R. purdomii* in China was simulated based on 53 current distribution points and 6 environmental variables. The AUC values for the model were between 0.994 and 0.995, and the AUC radios ranged from 1.870 to 1.920, suggesting that the MaxEnt model was accurate and reliable (Table 2).

Table 2. The AUC and AUC ratio values for the maximum entropy model of *R. purdomii*.

Climate Scenarios	AUC	AUC Radios
LGM	0.995	1.870
Mid-Holocene	0.994	1.877
Current	0.994	1.914
SSP126_2050s	0.994	1.908
SSP126_2070s	0.994	1.920
SSP585_2050s	0.995	1.900
SSP585_2070s	0.994	1.901

The cumulative contributions of topographic variables, temperature-related variables, and precipitation-related variables to the model were 44.2%, 42.3%, and 13.6%, respectively (Table 1). Among the variables, the contribution of slope (SLP), isothermality (Bio03), temperature seasonality (Bio04), altitude (ALT), annual precipitation (Bio12), and aspect (ASP) to the predicted species distribution were 25.6%, 22.8%, 19.5%, 17.7%, 13.6%, and 0.9%, respectively. The results of the jackknife method showed that altitude (ALT) was the most influential environmental variable, followed by annual precipitation (Bio12) and temperature seasonality (Bio04) when only a single environmental variable was used, indicating that these environmental variables were important for the prediction of *R. purdomii* distribution (Figure 2). According to the response curves of the variables (Figure 3), it was suitable for the distribution of *R. purdomii* at an isothermality (Bio03) of 21–32, temperature seasonality (Bio04) of 7–9 °C, annual precipitation (Bio12) of 600–1100 mm, altitude (ALT) of 1500–3200 m, and slope (SLP) of 2.5–12°. The quantitative analysis indicated that the areas with low temperature seasonality, humid climate, high altitude, and certain slope are suitable for the survival of *R. purdomii*.

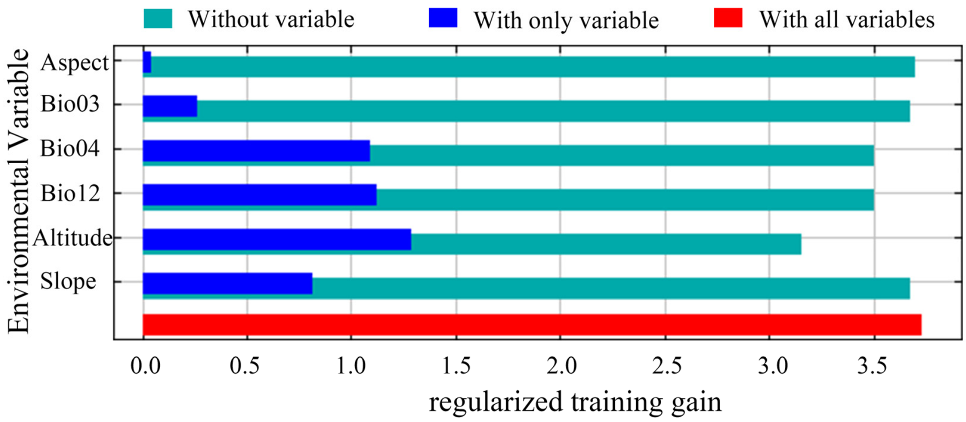

Figure 2. The importance evaluation of the six environmental variables related to *R. purdomii* distribution by using the jackknife method.

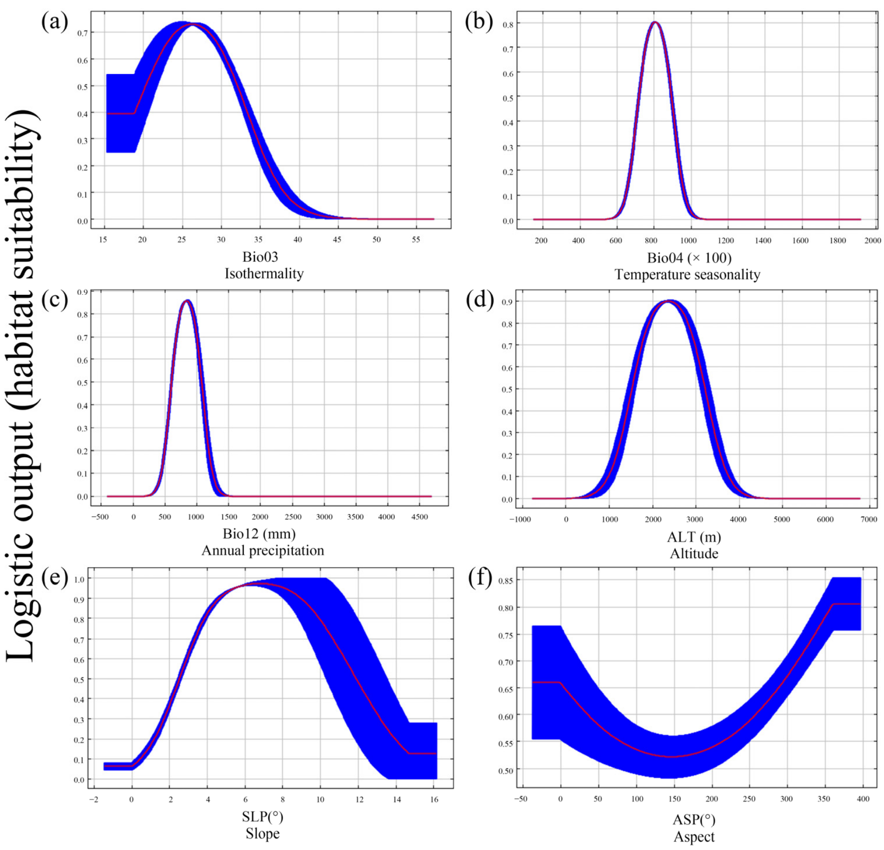

Figure 3. Response curves of the main environmental variables. Isothermality (**a**); temperature seasonality (**b**); annual precipitation (**c**); altitude (**d**); slope (**e**) and aspect (**f**). The red curves show the mean over 10 replicate runs, and blue bands show the standard deviation.

3.2. Distribution Shifts in Different Climate Scenarios

Potential distribution and changes under the LGM, Mid-Holocene, current, and future scenarios are presented in Figures 4–6 and Table 3. From the past to the future, the suitable distribution areas of *R. purdomii* showed a trend of expansion, except under the SSP126 (2050s) scenario. Under different scenarios, the low-suitable areas occupied more than half (62.54–67.66%) of the predicted suitable areas, whereas the high-suitable areas only accounted for 10.24–15.37% of all the suitable areas (Table 3).

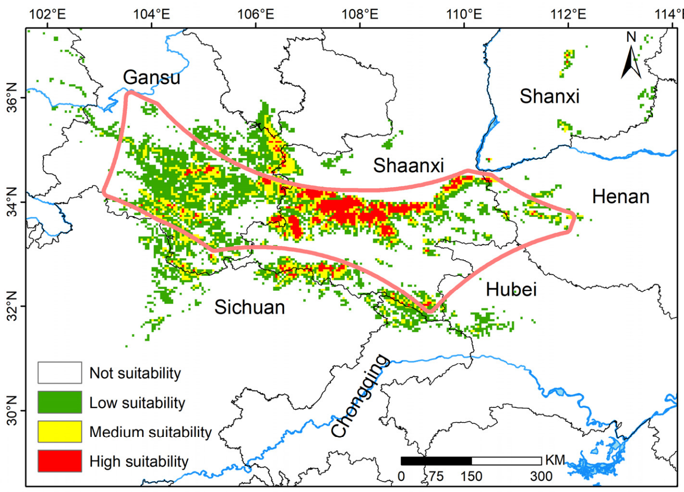

Figure 4. The potential distribution of *R. purdomii* under current climatic condition. The extent of occurrence (EOO) polygon (orange) of this species is also provided.

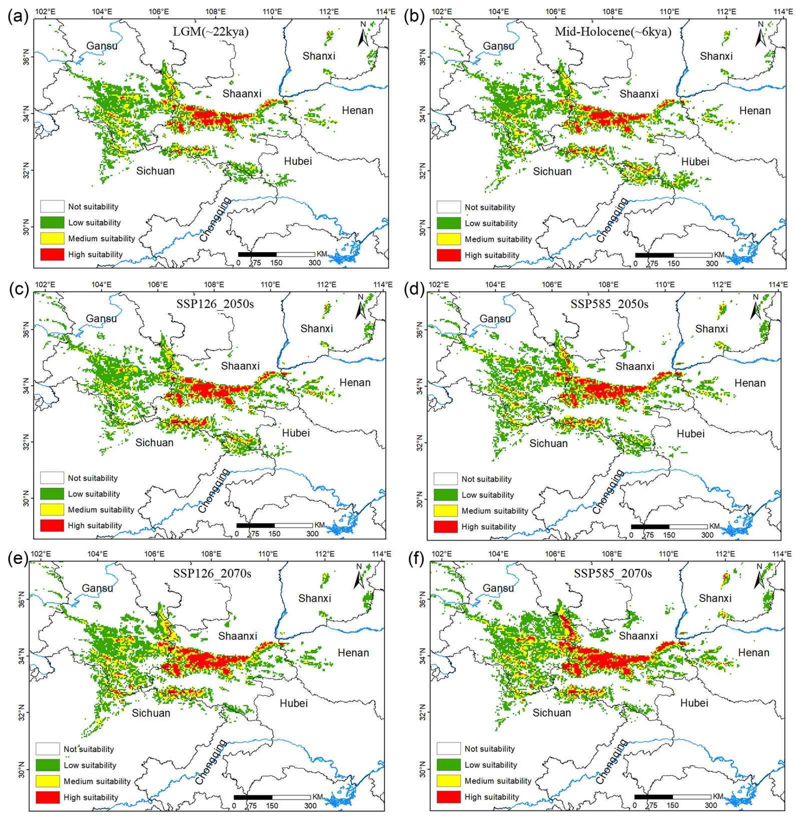

Figure 5. The potential distribution of *R. purdomii* under the two past climate scenarios and four future climate scenarios. LGM (**a**); Mid-Holocene (**b**); SSP126_2050s (**c**); SSP585_2050s (**d**); SSP126_2070s (**e**); SSP585_2070s (**f**).

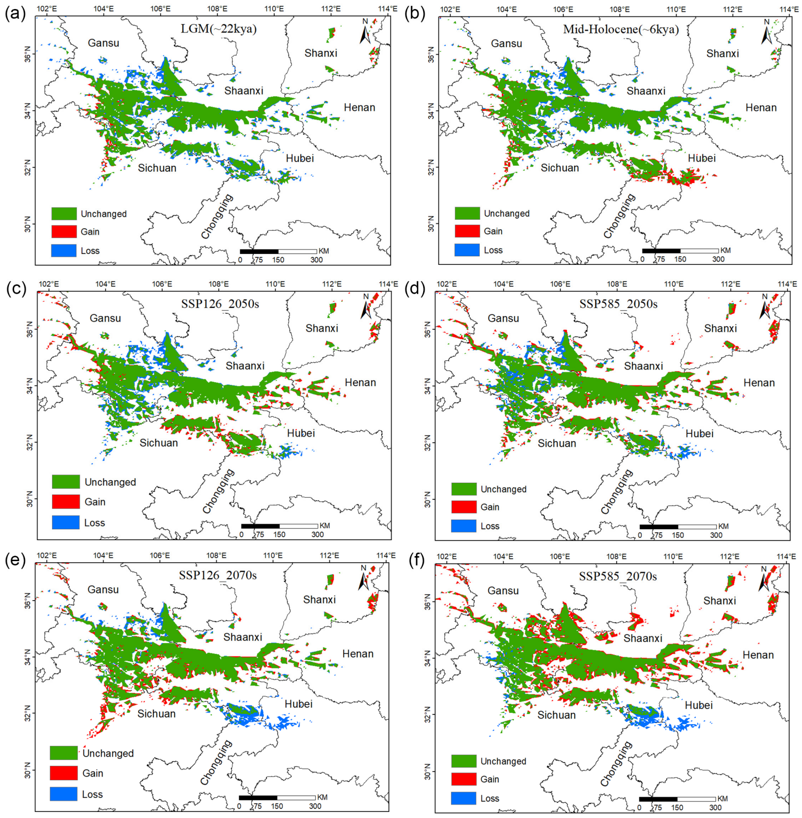

Figure 6. The predicted changes in the suitable areas of *R. purdomii* under different climate scenarios compared to the current condition. LGM (**a**); Mid-Holocene (**b**); SSP126_2050s (**c**); SSP585_2050s (**d**); SSP126_2070s (**e**); SSP585_2070s (**f**).

Table 3. The potential distribution areas of *R. purdomii* in the different periods and climate scenarios.

Period	Low Suitability		Medium Suitability		High Suitability		Total Suitable
	Area (10^4 km^2)	Percentage (%)	Area (10^4 km^2)	Percentage (%)	Area (10^4 km^2)	Percentage (%)	Area (10^4 km^2)
LGM	6.11	67.66	1.97	21.82	0.95	10.52	9.03
Mid-Holocene	6.78	66.73	2.34	23.03	1.04	10.24	10.16
Current	6.86	65.77	2.38	22.82	1.19	11.41	10.43
SSP126_2050s	6.93	66.64	2.23	21.44	1.24	11.92	10.40
SSP126_2070s	7.10	66.29	2.29	21.38	1.32	12.33	10.71
SSP585_2050s	6.86	63.58	2.47	22.89	1.46	13.53	10.79
SSP585_2070s	7.73	62.54	2.73	22.09	1.90	15.37	12.36

The current potential distribution of *R. purdomii* was primarily located in the QBM, including southern Shaanxi, southeastern Gansu, western Henan, northwestern Hubei, northeastern Chongqing, and northeastern Sichuan (Figure 4). The total suitable area amounted to 10.43×10^4 km^2. In particular, the low-suitable area occupied more than half (65.77%) of the predicted suitable area. Conversely, the high-suitable area only accounted for 11.41% of all the suitable area (Table 3).

The extent of occurrence (EOO) of *R. purdomii* is estimated to be 193,391 km^2. The area of occupancy (AOO) of *R. purdomii* is estimated to be 204 km^2 and the number of subpopulations is 33. The MaxEnt-predicted suitable area under the current climate scenario (104,300 km^2) is lower than the inferred EOO (Figure 4).

Compared to the current scenario, the habitat suitability of *R. purdomii* was probably low during the LGM and Mid-Holocene periods. During the LGM, the total habitat suitable area was probably 9.03×10^4 km^2, and the high-suitable area was probably 0.95×10^4 km^2.

During the Mid-Holocene, the total habitat suitable area was probably 10.16 × 10^4 km^2, and the high-suitable area was probably 1.04 × 10^4 km^2 (Table 3, Figure 5).

Under the SSP126 scenario, the potential suitable area of *R. purdomii* in the 2050s might be 10.40 × 10^4 km^2, 0.29% less than the current distribution area. The high-suitable area of *R. purdomii* would be predicted to be 1.24 × 10^4 km^2, and the medium-suitable area would be predicted to be 2.23 × 10^4 km^2 (Table 3, Figure 5). The potential suitable area of *R. purdomii* in the 2070s might be 10.71 × 10^4 km^2, 2.68% more than the current distribution area. The high-suitable area of *R. purdomii* would be predicted to be 1.32 × 10^4 km^2, and the medium-suitability area would be predicted to be 2.29 × 10^4 km^2.

Under the SSP585 scenario, the potential suitable area of *R. purdomii* in the 2050s might be 10.79 × 10^4 km^2, 3.45% more than the current distribution area. The high-suitable area of *R. purdomii* would be predicted to be 1.46 × 10^4 km^2, and the medium-suitability area would be predicted to be 2.47 × 10^4 km^2. The potential suitable area in the 2070s will attain a maximum value (12.36 × 10^4 km^2), 18.50% more than the current distribution area. The high-suitable area of *R. purdomii* would be predicted to be 1.90 × 10^4 km^2, and the medium-suitability area would be predicted to be 2.73 × 10^4 km^2 (Table 3, Figure 5).

The magnitude and direction of potential distribution shifts of *R. purdomii* varied during the different periods. The suitable distribution areas of *R. purdomii* concentrated continuously in the QBM, and the distribution changes were mainly limited to the marginal areas of species distribution (Figures 5 and 6). The suitable distribution areas of *R. purdomii* showed the pattern of northward shift and west–east migration in response to climate change. From the past to the future, the potential distribution areas will shrink in the western and southern margin, and a new suitable area will expand in the northern and eastern regions.

4. Discussion

Mountain plant species might be relatively more sensitive to climate change. This study predicted the potential impacts of climate change on the endemic and vulnerable species *R. purdomii* in the QBM of Central China. This is the first study to analyze the range shifts and climate change vulnerability of *R. purdomii* based on the species distribution model. To ensure the model accuracy, the occurrence data and environmental variables have been carefully selected. Moreover, model parameters optimization and evaluation were made by using the Kuenm package. Finally, the AUC and AUC radios values indicated the high prediction accuracy of the MaxEnt model.

4.1. Relationship between Habitat Suitability and Environmental Variables

In this study, we found that the distribution of *R. purdomii* was concentrated in the QBM. Our predicted current distribution matched well with the actual distribution of this species. The main environmental variables affecting the habitat suitability of *R. purdomii* were altitude, temperature seasonality, annual precipitation, slope, and isothermality. The contribution of topographic variables and temperature-related variables to the model accounted for 44.2% and 42.3%, respectively, indicating that topography and temperature had a higher impact on *R. purdomii* distribution than precipitation. Our findings are consistent with several other studies in the QBM region. Previous studies have shown that temperature may be a more important factor than precipitation determining tree species (e.g., *Larix chinensis*) distribution and growth in the QBM [18,44,45]. A recent study by Shrestha et al. [46] found that topographical complexity and temperature seasonality had a great impact on the diversity and distribution of *Rhododendron* in China. Our results support this pattern. Furthermore, our results also indicate that *R. purdomii* prefers to survive in areas with low temperature seasonality, humid climate, high altitude, and certain slope, which is consistent with the niche properties of alpine evergreen *Rhododendron* species [8]. The results can provide a guideline for habitat conservation and restoration of this vulnerable species.

The impact of global climate change on plant distribution is immensely complex and uncertain. Aside from the bioclimatic and topographic variables, other factors, such as soil type, microhabitat, species interaction, dispersal limitation, and land use change, can also have relatively important impacts on the distribution of *Rhododendron* species [6,14,28]. Furthermore, the spatial resolution of the WorldClim data will affect the predictive performance. As the dominant factors affecting species distribution at a large scale, climate and topography have been used in our current analysis. Although there may be uncertainty in the projection, our result can provide the general distribution shifts of *R. purdomii*. In accordance with the ecological characteristics of *R. purdomii*, a selection of more environmental variables and different models may make the predictions better in further research.

4.2. Distribution Shifts under Climate Change

Our results showed that *R. purdomii* was restricted to the QBM of Central China under different climate scenarios, indicating that these areas could potentially be long-term climate refugia for *R. purdomii*. Due to the complex topography of the QBM, this region hosts diverse microclimates that have facilitated the survival of numerous endemic and relict species during climate change [16,21,47]. Moreover, compared to the current distribution, the habitat suitability of *R. purdomii* was probably low during the LGM and the Mid-Holocene. In the future, the suitable distribution areas of *R. purdomii* would expand under the three future climate scenarios, except the SSP126 (2050s) scenario. Previous studies have shown that the effects of climate change on *Rhododendron* species are often species-specific [6,28]. Our results suggest that *R. purdomii* may have a certain adaptive potential to climate change. However, the high-suitable habitat proportion was relatively lower under different scenarios, only 10.24–15.37% of all the suitable areas, indicating that *R. purdomii* will also be vulnerable to climate change. Therefore, habitat conservation and management is necessary in all the current distribution sites.

The QBM is located in the transitional zone from the subtropical to the warm temperate zone of China, which is sensitive to climate changes [17,48]. Several recent studies have suggested that the anthropogenic climate changes are already impacting plant species and vegetation dynamics in the QBM [18,19,44,45]. For example, Zhang et al. (2022) [19] revealed that the evergreen vegetation cover in the QBM continued to move northwards with increasing winter temperature in recent decades. Zhang et al. (2020) [49] predicted that the suitable area of evergreen broadleaved tree *Cyclobalanopsis glauca* would shift to higher latitude in this region under future climate change. In our study, the potential distribution areas of *R. purdomii* also showed an increasing trend in the northern regions under future climate scenarios, which have been frequently reported in the other species [6]. Meanwhile, the suitable distribution areas of *R. purdomii* showed the trend of west–east migration from the past to future climate scenarios, continuing to decline in the western distribution, whereas expanding in the eastern side. Similarly, distribution shift in a west–east direction was also found for other tree species in this region, such as *Pinus bungeana* [21]. It is probably due to the complex geological and climatic characteristics of the QBM, which run in an east–west direction in Central China. In addition, a recent study found that the warming-induced range shifts of tree species showed substantial difference and species-specific distribution limits in the Qinling Mountains [48]. Our findings reveal that the distribution shifts of plant species are multi-directional and complex in response to climate change, supporting previous studies [4,50]. Further research involving more species will strengthen our understanding of the range shifts of plant species associated with climate change in the QBM region.

In this study, the distribution changes of *R. purdomii* were mainly limited to the marginal areas of species distribution. Wang et al. (2020) [17] also showed that vegetation dynamics in the marginal areas of the Qinling Mountains were particularly sensitive to climate change. As compared to central populations, the marginal populations are expected to have a smaller population size and greater spatial isolation, which may exhibit lower genetic diversity and higher genetic differentiation [21,51]. Consequently, the marginal populations often have reduced fitness and adaptive potential, with a higher risk of local extinction under climate change [52]. *R. purdomii* is a long-lived woody species with slow growth rate, fragmented habitat, and weak dispersal capacity, making it difficult for marginal populations to adapt to rapid climate change [10,23]. In addition, the marginal habitat plays a crucial role in the evolution and adaptation of plant species in the face of climate change [53]. Therefore, the marginal populations and habitats of *R. purdomii* (e.g., southeastern Gansu, western Henan) should have priority for monitoring and management.

4.3. Conservation Strategies for R. purdomii

R. purdomii has been classified as vulnerable in the Red List of China's Higher Plants [26], and thus, it is necessary to develop effective conservation strategies for this species. According to previous studies and our field surveys, we found that human activities (e.g., tourism development, illegal collection), poor regeneration, small population size, and habitat fragmentation have significantly depleted some wild populations of *R. purdomii* [23,25]. However, special management actions and conservation plans for this species are still lacking. To ensure the long-term conservation of *R. purdomii*, the following strategies are recommended based on our current modeling.

Effective in situ conservation measures need to be implemented in all the current distribution sites of *R. purdomii*. The QBM has been predicted as the long-term suitable area for *R. purdomii* based on our modeling. Therefore, adaptive measures are needed to ensure that the suitable habitats are protected, including enhancing the effectiveness of protected areas, long-term monitoring, developing low-impact ecotourism, and raising public awareness of plant conservation [11,27]. The predicted suitable habitats under future climate conditions should be examined as priority areas for assisted migration and species introduction [54]. Moreover, ex situ conservation measures, such as botanical gardens and arboreta, can be used for the conservation of germplasm resources. Further research of population ecology, phylogeography, landscape genomics, and common garden experiments can facilitate more precise assessments of climate adaptation and help guide the long-term conservation of *R. purdomii* [55].

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