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Predicting the impact of climate change on the distribution of *rhododendron* on the qinghai-xizang plateau using maxent model

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Amid the ongoing trend of global warming, the distribution of habitable areas for *Rhododendron* is facing significant risks. To investigate the possible spatial distribution of *Rhododendron* on the Qinghai-Xizang Plateau in light of future global warming scenarios, we employed the Maximum entropy model (MaxEnt model) to map its suitable habitat using geographic distribution data and environmental factors projected for 2050s and 2070s, considering three representative concentration pathway (RCP) scenarios, while identifying the key factors influencing their distribution. The results show that: [1] The area under curve (AUC) values of the five *Rhododendron* were all greater than 0.98, indicated that the model prediction effect was excellent; [2] Isothermality is the most important environmental factor affecting the distribution of *Rhododendron* (excluding *Rhododendron przewalskii*). The most important environmental factor for *Rhododendron przewalskii* is altitude (alt: 51%), with an optimum range of 2700–3300 m, and *Rhododendron trichostomum* are affected by altitude (alt 18%), with an optimum range of 3200–3900 m. *Rhododendron przewalskii* (bio12: 21%) and *Rhododendron trichostomum*(bio12: 19%) are also affected by annual precipitation, and *Rhododendron laudandum*(bio12: 6%) is less affected by annual precipitation, The optimal amount of precipitation is 400–500 mm as well as 500–800 mm. *Rhododendron przewalskii* and *Rhododendron trichostomum* are suitable for survival in high altitude, semi-arid areas [3]. The suitable areas for survival for *Rhododendron przewalskii*, *Rhododendron trichostomum*, *Rhododendron hypenanthum*, and *Rhododendron nyingchiense* is expanding, while the suitable areas for survival for *Rhododendron laudandum* is shrinking [4]. The optimal zone for *Rhododendron przewalskii* is primarily found in the eastern section of the Qinghai-Xizang Plateau, while suitable areas for survival for the other four *Rhododendron* species are predominantly located in the southern region of the same plateau. Therefore, these regions will be designated as the primary conservation zones for in-situ preservation. The results of the study provide a basis for the in situ conservation of *Rhododendron* in response to global warming, relocation conservation, and the construction of nature reserve communities and ecological corridors.

Keywords *Rhododendron*, The Qinghai-Xizang plateau, Climate change, MaxEnt model, Potential distribution

It is a widely recognized fact that the 21st century presents a significant challenge to both humans and ecosystems in the form of global climate change[1]. According to a recent report released by the Intergovernmental Panel on Climate Change (IPCC), the earth's average temperature has increased by approximately 1.5 °C compared to levels before industrialization, impacting the survival and geographical distribution of various species[2,3]. Numerous research studies have indicated that species are able to cope with the effects of climate change by adjusting their ecological niches and migrating towards higher altitudes or latitudes[4,5]. However, the ecological niches of species in different climates may evolve slowly compared to changes in climate. The gradual increase in temperature may lead to the extinction of certain species with limited ability to migrate. In a recent analysis

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of the suitable habitat for the coast redwood (*Sequoia sempervirens D. Don*), it was observed that its habitat has significantly reduced in size, putting the species at risk of extinction[6]. Most plants on the Qinghai-Xizang Plateau are at risk of extinction under future warming scenarios. Therefore, it is crucial to accurately forecast and understand the distribution of suitable habitats for endangered species in future scenarios, at both spatial and temporal scales, in order to conserve species diversity[7,8].

The Qinghai-Xizang Plateau, also referred to as the "Third Pole of the Earth"[9,10], can be found in the western region of China with an average elevation exceeding 4000 m[11,12]. Greenhouse gas emissions contribute to global warming[13,14], and studies indicate that from 1961 to 2020, the annual average temperature on the Qinghai-Xizang Plateau is projected to increase by 0.35 °C per decade, which is more than double the global warming rate over the same timeframe. Additionally, the annual mean temperature on the Qinghai-Xizang Plateau is forecasted to rise by 1.6 °C to 2.0 °C by the year 2050. By the 2070s, the mean annual temperature on the Qinghai-Xizang Plateau is expected to increase by 1.2 °C to 3.0 °C. Climate models suggest that global warming could potentially exceed 6.5 °C by the end of the century[9]. Alpine plants are particularly susceptible to the impacts of global warming due to their evolutionary adaptation to cold environments[15,16]. Species on the Qinghai-Xizang Plateau exhibit high sensitivity to climate variations. Research indicates that six types of alpine plants in the Arctic exhibit varied responses to global warming, specifically affecting perennials and annuals, resulting in reduced suitable habitats. Consequently, a decline in the alpine plant population is anticipated in the future due to the effects of global warming[17]. Moreover, plants in alpine regions face greater challenges compared to those in lower altitudes and warmer climates[18].

The genus *Rhododendron* belongs to the family *Rhododendronaceae* and there are eight species worldwide, divided into eight subgenera. These species are widely distributed in Europe, Asia and North America. *Rhododendrons* have great ornamental and medicinal value[19], some of the plants in the genus *Rhododendron* can be used as a medicinal herbit, some plants of the genus *Rhododendron* are edible and can be used as a cash crop. *Rhododendron*, as one of the most prevalent woody plants in China, plays a crucial role in stabilizing slope topography and protecting river basins due to its significant biomass, flexible soil requirements, adaptability, and the formation of a well-developed lateral root system that intertwines effectively[20]. Additionally, *Rhododendron* exhibits a high capacity for enriching heavy metals such as lead, cadmium, and zinc, making it valuable for the remediation of heavy metal contaminated soil. Research on *Rhododendron* has focused more on morphological identification, plant metabolism, and molecular level[21]. Little research has been done on predicting the distribution of *Rhododendrons* and identifying suitable habitats[22]. In China, *Rhododendrons* are mainly distributed in the southwest, of which Yunnan, Sichuan and Xizang are the most abundant. It is important to understand the spatial distribution pattern of *Rhododendron* on the Qinghai-Xizang Plateau[23].

The quantification of the correlation between species occurrence and environmental variables through ecological niche modeling helps describe a species ecological niche or habitat suitability, providing insights into changes in species distribution influenced by climate and other environmental factors[12,24]. Currently, popular ecological niche models include the Genetic Algorithm Rule Set Model (GARP), Bioclimatic Analysis and Prediction System Model (BIOCLIM), Random Forests Models (RFs), and the MaxEnt model. Among these, the MaxEnt model is widely utilized in various fields by scholars globally due to its user-friendly interface, high accuracy in predictions, simplicity in operation, and strong explanatory abilities[25–27]. In previous studies that the model is widely used on the Qinghai-Xizang Plateau. Some researchers utilized the MaxEnt model to predict the current and future potential distribution of six musk species on the Qinghai-Xizang Plateau[28].

In this study, we selected five species of *Rhododendron* that are common on the Qinghai-Xizang Plateau, the species distribution of *Rhododendron* on the Qinghai-Xizang Plateau has not been previously studied. Geographic distribution data along with environmental factors were utilized to forecast both current and future distributions on the Qinghai-Xizang Plateau in light of climate change scenarios, employing the MaxEnt model, where eight soil factors were added to increase the comprehensiveness of the research. The objectives of this study were[1] Determine the existing distribution of *Rhododendron* in the context of global warming;[2] Analyze the primary environmental elements that influence Rhododendron distribution;[3] Clarify changes in the area of suitable habitat under future climate change.

Materials and methods

Data and variable sources

This research acquired distribution data of five *Rhododendron* species from various sources:[1] CNKI database (http://www.cnki.net/ accessed on 7 October 2022);[2] China Digital Herbarium (https://www.cvh.ac.cn/ accessed on 7 October 2022);[3] NSII China National Herbarium Resource Leveling (http://www.nsii.org.cn/2017/home.php accessed on 7 October 2022);[4] Global Biodiversity Information Facility (https://www.gbif.org/zh/);[5] China Plant Image Library (http://ppbc.iplant.cn/ accessed on 7 October 2022). In cases where precise latitude and longitude coordinates were absent in the recorded data, we utilized Google Earth (http://ditu.google.cn/ accessed on 7 October 2022) to determine these coordinates based on described geographic positions. To mitigate spatial autocorrelation effects resulting from close sample point proximity, ENMTools were employed to eliminate redundant points. Data on the geographical distribution of the five species of *Rhododendron* are given in Table 1. The sample latitude and longitude coordinates were saved in an excel file and converted to CSV format for MaxEnd model construction (Fig. 1).

We obtained 19 bioclimatic factors and elevation variables from the global climate database WorldClim (version 1.4) (http://www.worldclim.org/ accessed on 7 October 2022) that have been most frequently used to study plants on the Qinghai-Xizang Plateau in recent years, with a spatial resolution of 30 arcseconds (approximately 1 km). Additionally, 8 soil variables were obtained from the National Tibetan Plateau Data Center (https://data.tpdc.ac.cn/home accessed on 7 October 2022), resampled to a spatial resolution of 30 arcseconds (approximately 1 km). Future climate data were determined using the CCSM4 model with the most

Species	Plot number	Optimized point number	Longitudinal range(°E)	Latitudinal range(°*N*)
Rhododendron nyingchiense	37	31	93.7–95.8	29.61–29.9
Rhododendron przewalskii	190	188	97.0-104.2	28.5–37.3
Rhododendron laudandum	60	52	92.2–98.0	27.7–32.4
Rhododendron hypenanthum	68	58	84.8–95.7	28.0-29.8
Rhododendron trichostomum	306	273	90.4-102.5	27.0-38.4

Table 1. Geographical range and plot information of five species of *Rhododendron* on the Oinghai-Xizang plateau.

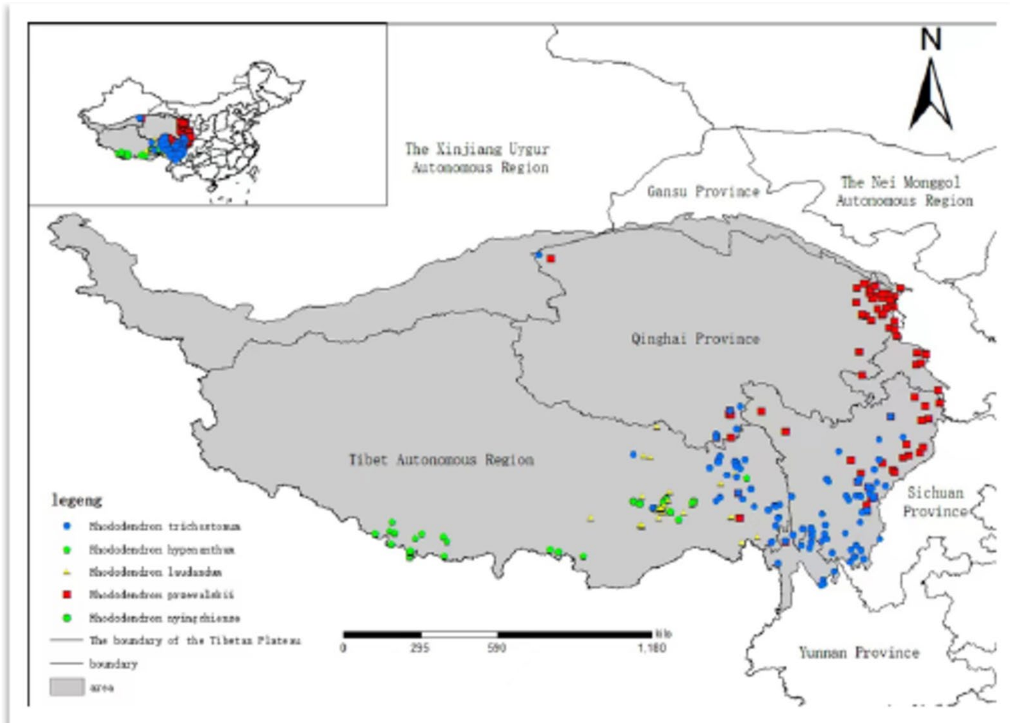

Fig. 1. Modern occurrence sites of the 5 *Rhododendron* species.

favorable climate effects in China for years 2050s and 2070s. Three different concentration pathways (RCP2.6, RCP6.0, and RCP8.5) were selected to predict the potential extent of climate change. These pathways correspond to low, medium, and high levels of greenhouse gas (GHG) concentrations in the future, respectively. Lastly, all bioclimatic variables were converted to ASCII format for MaxEnt analysis. (Table S1)

Environmental variable processing

The issue of multicollinearity with climatic factors may impact our accuracy to assess the connection between species and their environment[29]. Past research has highlighted the seriousness of this problem with bioclimatic variables. To address this, We calculated the Pearson correlation coefficients between the environmental factors and set the correlation coefficients at a threshold of 0.8[30], retaining those with correlation coefficients less than 0.8, of which those with correlation coefficients greater than 0.8 were retained with the highest contribution, while removing those with a contribution of zero[31].

MaxEnt parameter optimization

The latitude and longitude data of five *Rhododendron* species, along with the filtered environmental variables, were entered into the MaxEnt software. The model was configured with the following settings: 25% of the samples were designated as the test set, while the remaining 75% comprised the training set. The number of replicates was specified as 10, with the replicates run type set to Bootstrap. The "jackknife" method was employed to evaluate the impact of environmental factors. The maximum number of iterations was limited to 5000[32]. Output format was selected as "Logistic", and the file type was designated as "ASC". All other parameters were kept at their default values[33].

MaxEnt model evaluation

Researchers utilized the receiver-operating characteristic curve (AUC) to evaluate the precision of the species distribution model[34]. The AUC presents the extent of accuracy, with values ranging from 0 to 1. A higher AUC value signifies increased model accuracy[35]. An AUC value below 0.7 indicates poor prediction results, while 0.7 to 0.8 suggests an average outcome. The model is considered better with an AUC value between 0.8 and 0.9 and excellent with a value exceeding 0.9[27,36–38].

Classification of habitat suitability ranks

Species suitability values modeled by MaxEnt ranged between 0 and 1[39], with higher values indicating greater suitability in the specified area. After performing 10 repetitions of the MaxEnt model, a threshold value (10 percentile training presence Logistic threshold) was applied to the "maxent-results" to distinguish unsuitable from suitable regions. The five *Rhododendron* species were reassigned in the ArcGIS software, dividing suitable areas into three categories (lowly suitable region, moderately suitable region, and highly suitable region). The suitability indices were then classified into four ranks. (Table S3)

Results

Model selection and evaluation

According to the ROC curve analysis, the average AUC value for current and future predictions of five different *Rhododendron* species was determined through 10 repetitions, higher AUC values indicate high predictive accuracy of model results. The findings revealed that *Rhododendron nyingchiense*(AUC = 0.988), *Rhododendron przewalskii*(AUC = 0.985), *Rhododendron laudandum*(AUC = 0.989), *Rhododendron hypenanthum*(AUC = 0.995), and *Rhododendron trichostomum*(AUC = 0.985) had highly accurate potential distribution results as predicted by the model (Fig. 2).

Critical environmental factors

The MaxEnt jackknife test tool was used to assess the effects of various environmental variables on predicting the distribution of five species of *Rhododendron* (Fig. 3, Figure S1). We analyzed the environmental factors of five species of *Rhododendron*, the results showed that the distribution of *Rhododendron* was mainly influenced by isothermality (Bio3), altitude (Alt), annual precipitation (Bio12) and some soil factors. Figure 3 illustrates that isothermality significantly affect the distribution of *Rhododendron*, with the exception of *Rhododendron przewalskii*. With the combined contribution rate of isothermality reaching 54.5%. The existence probability of *Rhododendron nyingchiense*, *Rhododendron hypenanthum*, and *Rhododendron trichostomum* reaches the maximum when isothermality is 55%. The existence probability still unchange as the isothermality increases. The existence probability of *Rhododendron laudandum* reached the maximum when the isothermality reached 44%, The existence probability still decreases as the isothermality increases. The existence probability of *Rhododendron przewalskii* reached the maximum when the isothermality reached 34%. The existence probability still decreases as the isothermality increases (Fig. 4).

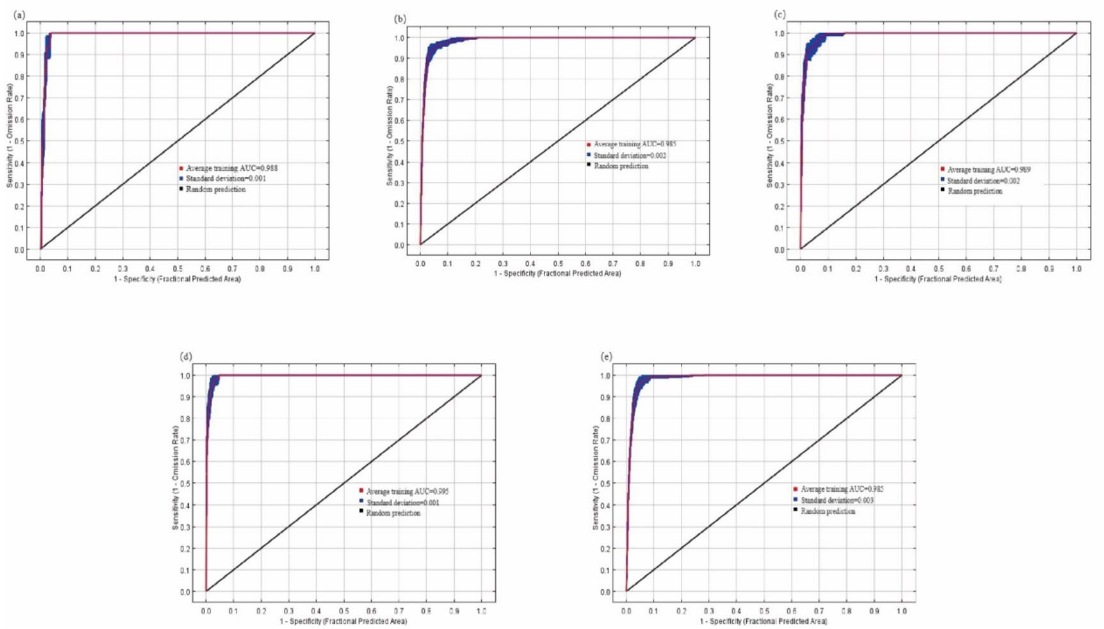

Fig. 2. Receiver operating characteristic (ROC) curve and average test AUC for accuracy analysis of *Rhododendron* by MaxEnt model under the current situation. (**a**) *Rhododendron ningchiense*, (**b**) *Rhododendron przewalskii*, (**c**) *Rhododendron laudandum*, (**d**)*Rhododendron hypenanthum*, (**e**) *Rhododendron trichostomum*.

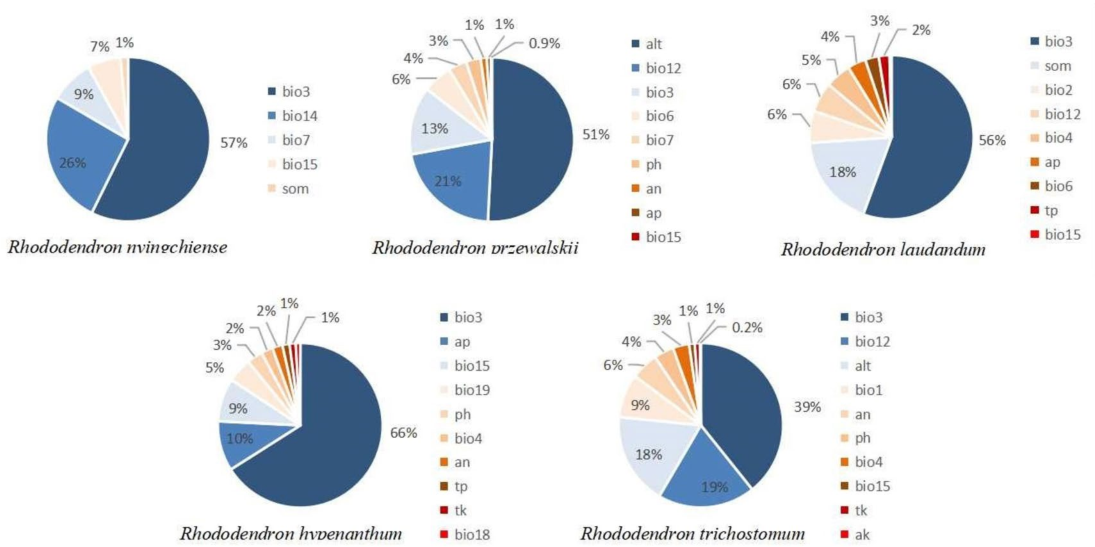

Fig. 3. Contribution of environmental factors to the growth and development of five *Rhododendron* species.

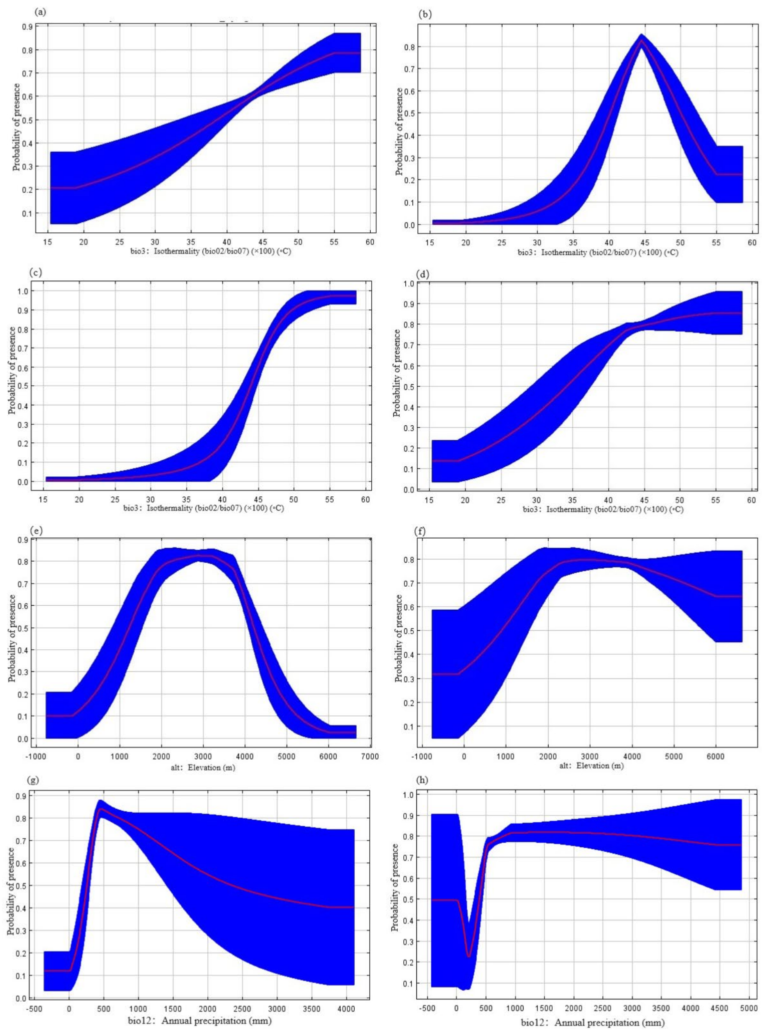

Fig. 4. Response curve of the key environmental factors(**a**: *Rhododendron nyingchiense*;**b**: *Rhododendron laudandum*;**c**: *Rhododendron hypenanthum*;**d**: *Rhododendron trichostomum*;**e**: *Rhododendron przewalskii*;**f**: *Rhododendron trichostomum*;**g**: *Rhododendron przewalskii*;**h**: *Rhododendron trichostomum*.

We further analyzed the effects of altitude, precipitation and soil factors on *Rhododendron*. The most important environmental factor of *Rhododendron przewalskii* was the altitude (alt:51%), with the optimum range of 2700–3300 m, and the optimum altitude range of the *Rhododendron trichostomum* (alt:18%) is 3200–3900 m. It is an important variable that affects most plants living on the Qinghai-Xizang Plateau. *Rhododendron* in the Qinghai-Xizang Plateau are particularly sensitive to altitude. Among the soil factors, *Rhododendron laudandum* was affected by soil organic matter (som: 18%) and effective phosphorus (ap: 4%), *Rhododendron hypenanthum* was affected by effective phosphorus (ap: 10%) and pH (pH: 3%), and *Rhododendron trichostomum* was affected by effective nitrogen (an: 6%) and pH (4%). *Rhododendron nyingchiense* was affected by soil organic matter (som: 2%), *Rhododendron przewalskii* (bio12: 21%) and *Rhododendron trichostomum* (bio12: 19%) are impacted by annual precipitation levels, The optimal amount of precipitation is 400–500 mm and 500–800 mm. In contrast, *Rhododendron laudandum* (bio12: 6%) is less influenced by annual precipitation, The optimal amount of precipitation is 400–500 mm (Fig. 4, Figure S2).

Current potential distribution of Rhododendron

The results show that the distribution of *Rhododendron nyingchiense*, *Rhododendron laudandum* and *Rhododendron hypenanthum* is wider than that of the other two species (Fig. 5). The total habitat area of *Rhododendron nyingchiense* covers 26.83×10^4 km^2, which represents 2.78% of the entire country's area. It is divided into a highly suitable region spanning 2.14×10^4 km^2 and a lowly suitable region covering 12.43×10^4 km^2. This habitat is primarily found in the southern regions of the Qinghai-Xizang Plateau, encompassing the southwest and southeast of Xizang, the north of Yunnan, and the southwest of Sichuan. The suitable habitat area for *Rhododendron laudandum* is 19.98×10^4 km^2, which represents 2.08% of the entire country's area. It is divided into a highly suitable region spanning 0.85×10^4 km^2 and a lowly suitable region covering 13.68×10^4 km^2. This habitat is primarily found in the eastern part of Xizang, including the southern part of Xizang and the western part of Xizang, and part of Sichuan. The suitable habitat area of *Rhododendron hypenanthum* is 15.06×10^4 km^2, which represents 1.57% of the entire country's area. It is divided into a highly suitable region spanning 0.37×10^4 km^2 and a lowly suitable region covering 12.49×10^4 km^2. This habitat is primarily found in the southern part of Xizang, the southwestern part of Sichuan, and the northern part of Yunnan. The suitable habitat area of *Rhododendron przewalskii* is 21. 18×10^4 km^2, which represents 2.20% of the entire country's area. It is divided into a highly suitable region spanning 0.50×10^4 km^2 and a lowly suitable region covering 14.74×10^4 km^2. This habitat is primarily found in the eastern part of the Qinghai-Xizang Plateau, including the eastern part of Qinghai, the south-central part of Gansu, and the north-central part of Sichuan. The suitable habitat area of *Rhododendron trichostomum* is 28. 17×10^4 km^2, which represents 2.93% of the entire country's area. It is divided into a highly suitable region spanning 1.09×10^4 km^2 and a lowly suitable region covering 18.85×10^4 km^2. This habitat is primarily found in the eastern part of Xizang, most parts of Sichuan, and the northern part of Yunnan (Table 2).

Future distribution prediction and fluctuation analysis of suitable habitats

In the future, considering the impacts of global warming, the habitat suitable for *Rhododendron trichostomum* and *Rhododendron przewalskii* will expand as CO_2 concentrations rise (Fig. 6). In comparison to the current

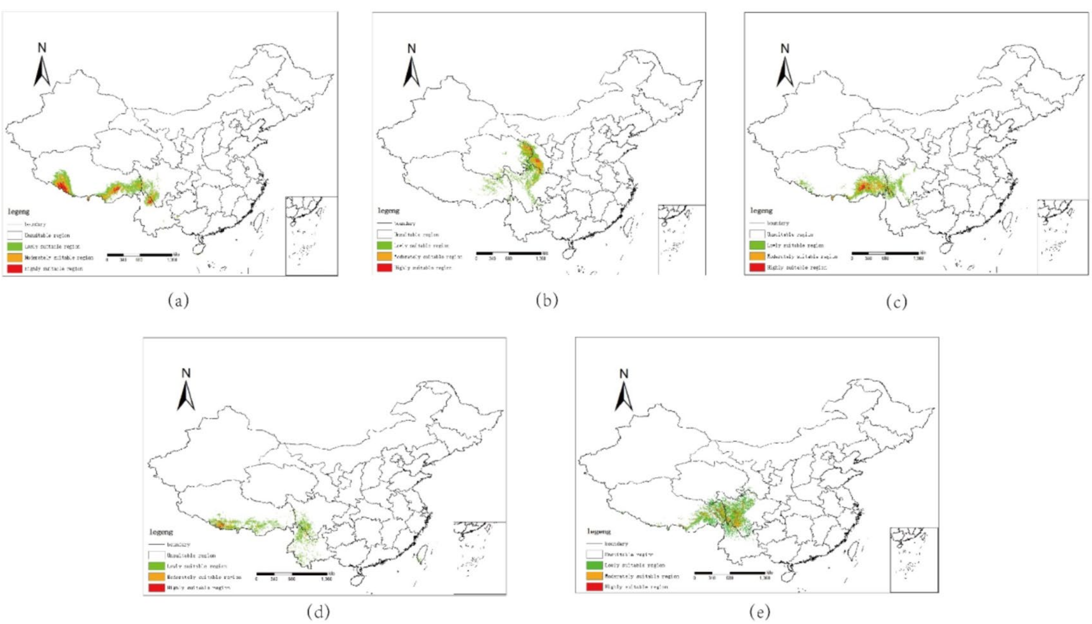

Fig. 5. Current distribution of MaxEnt models for five *Rhododendron* species in China, The color scale from white to red indicates the habitat suitability value from 0 to 1((**a**) *Rhododendron ningchiense*, (**b**) *Rhododendron przewalskii*, (**c**) *Rhododendron laudandum*, (**d**) *Rhododendron hypenanthum*, (**e**) *Rhododendron trichostomum*).

Species	Area (* 10^4 km^2)					Percentage (%)			
	HSR	MSR	PSR	USR		HSR	MSR	PSR	USR
Rhododendron nyingchiense	2.14	12.26	12.43	937.02		0.22	1.27	1.29	97.22
Rhododendron przewalskii	0.50	5.94	14.74	942.68		0.05	0.62	1.53	97.80
Rhododendron laudandum	0.85	5.45	13.68	943.87		0.09	0.57	1.42	97.92
Rhododendron hypenanthum	0.37	2.20	12.49	948.78		0.04	0.23	1.30	98.43
Rhododendron trichostomum	1.09	8.23	18.85	935.68		0.11	0.86	1.96	97.07

Table 2. Current habitat composition of five *Rhododendron* species in China under maxent model. HSR: highly suitable region; MSR: medium suitable region; PSR: poorly suitable region; USR: unsuitable region.

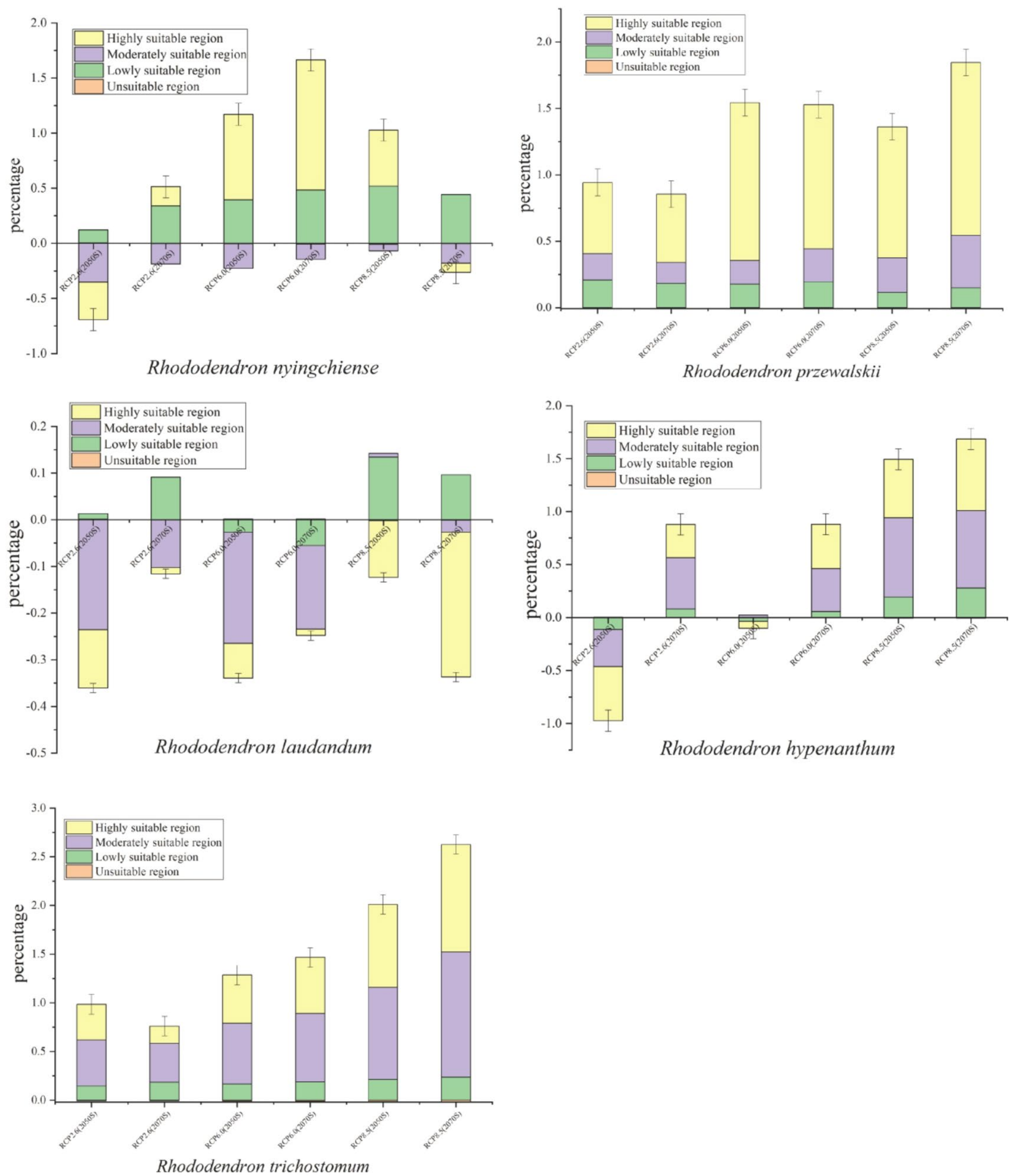

Fig. 6. Four different levels of fluctuation in China's future climate scenarios: Green, orange, red and blue represent the proportion of low, medium and high suitability areas and unsuitable habitats, respectively. A positive value indicates an increase in area and a negative value indicates a decrease in area.

suitable habitat area, the regions appropriate for these two species are projected to grow by 118% and 134.5%, respectively. The areas classified as highly suitable for *Rhododendron nyingchiense* are expected to increase by 42%, whereas the medium-suitable zones will experience a reduction of 20.5%. This species is primarily located in the southern and southwestern regions of the Qinghai-Xizang Plateau. For *Rhododendron laudandum*, both the medium and high suitable areas are anticipated to decrease by 12.5% and 16%, respectively, predominantly in the southern portion of the Qinghai-Xizang Plateau. Furthermore, the zones classified as medium and high suitability for *Rhododendron hypenanthum* will see increases of 20% and 9% in the future, respectively, with this species primarily found in southern Xizang, southwestern Sichuan, and northern Yunnan (Figs. 7 and 8). Comprehensive data can be found in Table S1.

Discussion

The MaxEnt model is widely used to estimate the habitat suitability of species and to predict the effects of global climate on the geographical distribution of specific species[40,41], and the model is widely used in disciplines such as conservation biology[27]. Environmental factors are categorized into biotic and abiotic factors. Abiotic factors mainly include climatic factors[42], and large-scale hydrothermal conditions (including temperature and precipitation) are important factors of species distributions[38]. While biotic factors include factors that are directly related to species distributions and usually act on species distributions at small spatial scales. Many studies have shown that the effects of biotic factors are negligible at larger scales[12,43]. Therefore, in this study, we modeled the distribution ranges and patterns of five *Rhododendron* species on the Qinghai-Xizang Plateau using common large-scale bioclimatic and soil factors.

Analysis of key environmental variables

Environmental variables consist of abiotic factors and biological factors. Abiotic factors primarily include climatic variables, which mimic the spatial distribution pattern and species range on a large scale. We used ArcGIS software and MaxEnt model to analyze the relationship between key environmental factors and the existence probability of *Rhododendron*. The results showed that: in addition to *Rhododendron przewalskii*, isothermality is the most important environmental variable affecting the remaining four *Rhododendron*. From the current distribution of the five *Rhododendron* species. The *Rhododendron przewalskii* is mainly distributed in the eastern part of the Qinghai-Xizang Plateau, while the other four species are distributed in the southern part of t the Qinghai-Xizang Plateau. Species specificity and differences in distribution areas can affect the contribution of environmental factors[40]. This explains the different contributing factors affecting species distribution. From the studies that have been done: Isothermality = (Mean Diurnal Range / Temperature Annual Range)×100. Some researchers investigated the potential geographical distribution of two peony species under climate change. The results show that temperature seasonality and isothermality made the greatest contributions to the distribution model for *P. delavayi* relative to other variables. Greater isothermality indicates a greater diurnal temperature difference in plants. Increased isothermality guarantees that plants can benefit from higher daytime temperatures for photosynthesis. While lower nighttime temperatures minimize energy usage for respiration, ultimately aiding in nutrient absorption by the plant's root system, promoting plant growth[44].

Rhododendron przewalskii and *Rhododendron trichostomum* thrive in high-altitude region. Many studies have shown that altitude is the most influential factor in plant distribution on the Qinghai-Xizang Plateau, a previous study conducted a quantitative synthesis of various environmental factors using 400 variables and 1900 species. The study revealed that temperature, precipitation, and altitude were the most commonly studied factors[45]. For terrestrial species, precipitation, temperature, and proximity to water were the most influential factors. Our results also suggest that altitude is a key factor influencing species distribution. With the importance of each variable changing depending on how often they were tested and the specific species[46]. Altitude usually interacts with temperature and light and has a significant effect on the accumulation of metabolites and nutrients in alpine plants. Some researchers investigated the relationship between niche breadth and phylogenetic characteristics of eight species of *rhubarb* on the Qinghai-Xizang Plateau[47]. The results show that altitude is the most important environmental variable affecting six plant species.

Rhododendron przewalskii and *Rhododendron trichostomum* thrive in semi-arid regions. From previous studies that plant respiration and transpiration are directly influenced by temperature and precipitation, impacting plant growth and development. The hydrothermal conditions, including temperature and precipitation plays a significant role in determining the distribution of species across large areas. Therefore, the distribution of the five *Rhododendron* plants is primarily impacted by climate change[46].

Additionally, prior studies suggest that abiotic factors have a more significant impact on *Rhododendron* species than soil factors. This study investigated the influence of various soil conditions, particularly those on the Qinghai-Xizang Plateau. Soil composition variations directly affect their growth. *Rhododendron laudandum* was impacted by soil organic matter (SOM: 18%) and available phosphorus (AP: 4%), *Rhododendron hypenanthum* by available phosphorus (AP: 10%), and *Rhododendron trichostomum* by available nitrogen (AN: 6%). Soil organic matter provides soil fertility retention and buffering qualities, available phosphorus supplies the soil with phosphorus and enhances plant growth, while available nitrogen is a key indicator of soil nitrogen fertility and is closely linked to crop growth. The findings suggest that *Rhododendrons* in this area exhibit specific soil preferences. Consequently, this research serves as a significant demonstration of how environmental factors can influence the distribution of *Rhododendrons* species in the future[48] (Fig. 8).

Changes in suitable habitat for 5 rhododendrons on the Qinghai-Xizang plateau

Over the next few decades, significant warming will be felt across the entire Qinghai-Xizang Plateau[9,28]. Plant growth and distribution in alpine ecosystems will be especially affected by temperature, as it is a major limiting factor[49,50]. Most of the available studies show that the area of suitable habitat for most alpine plants is contracting,

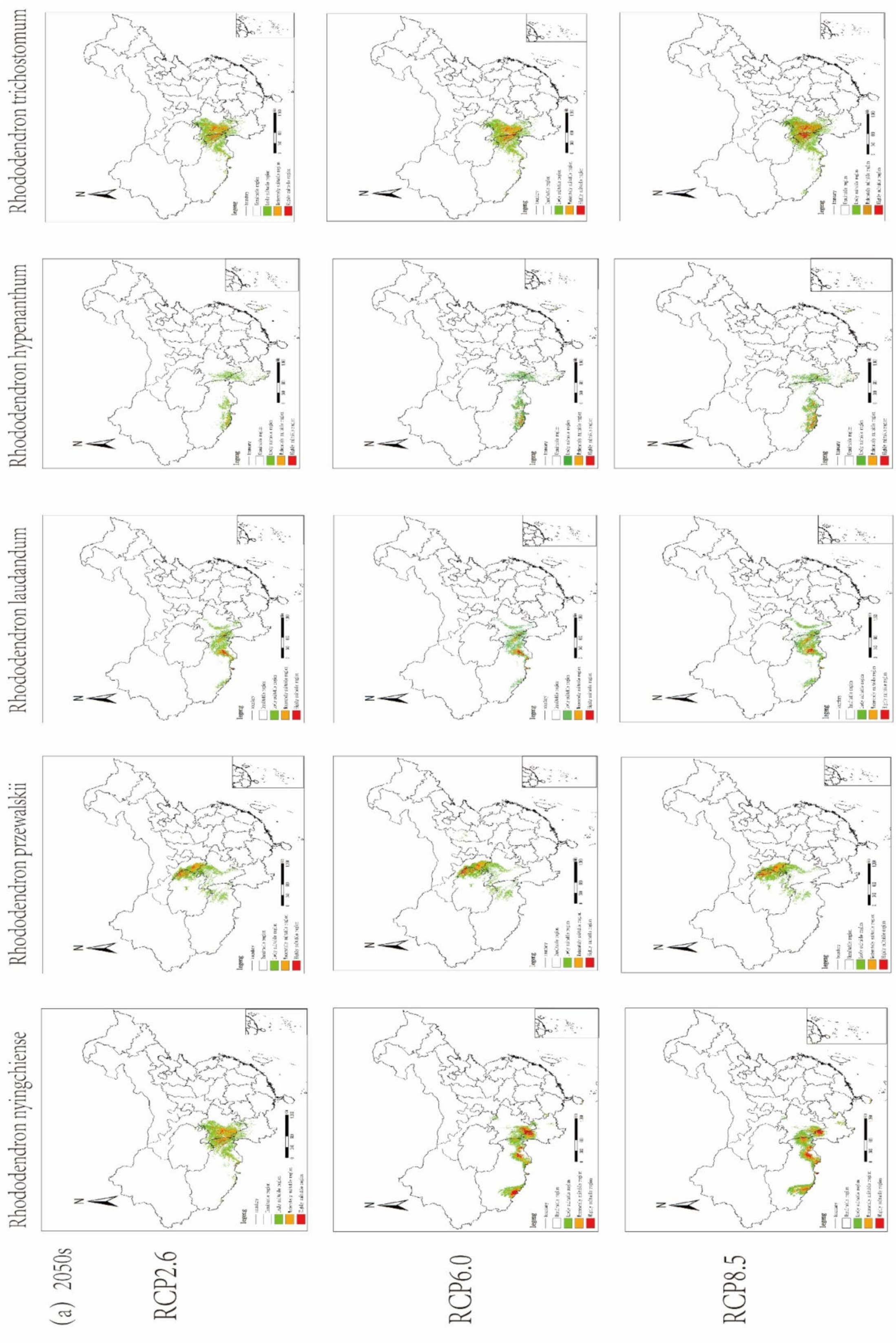

Fig. 7. (a) Prediction of the suitable range of the five species of *Rhododendron* in 2050s. RCP representative concentration pathway.

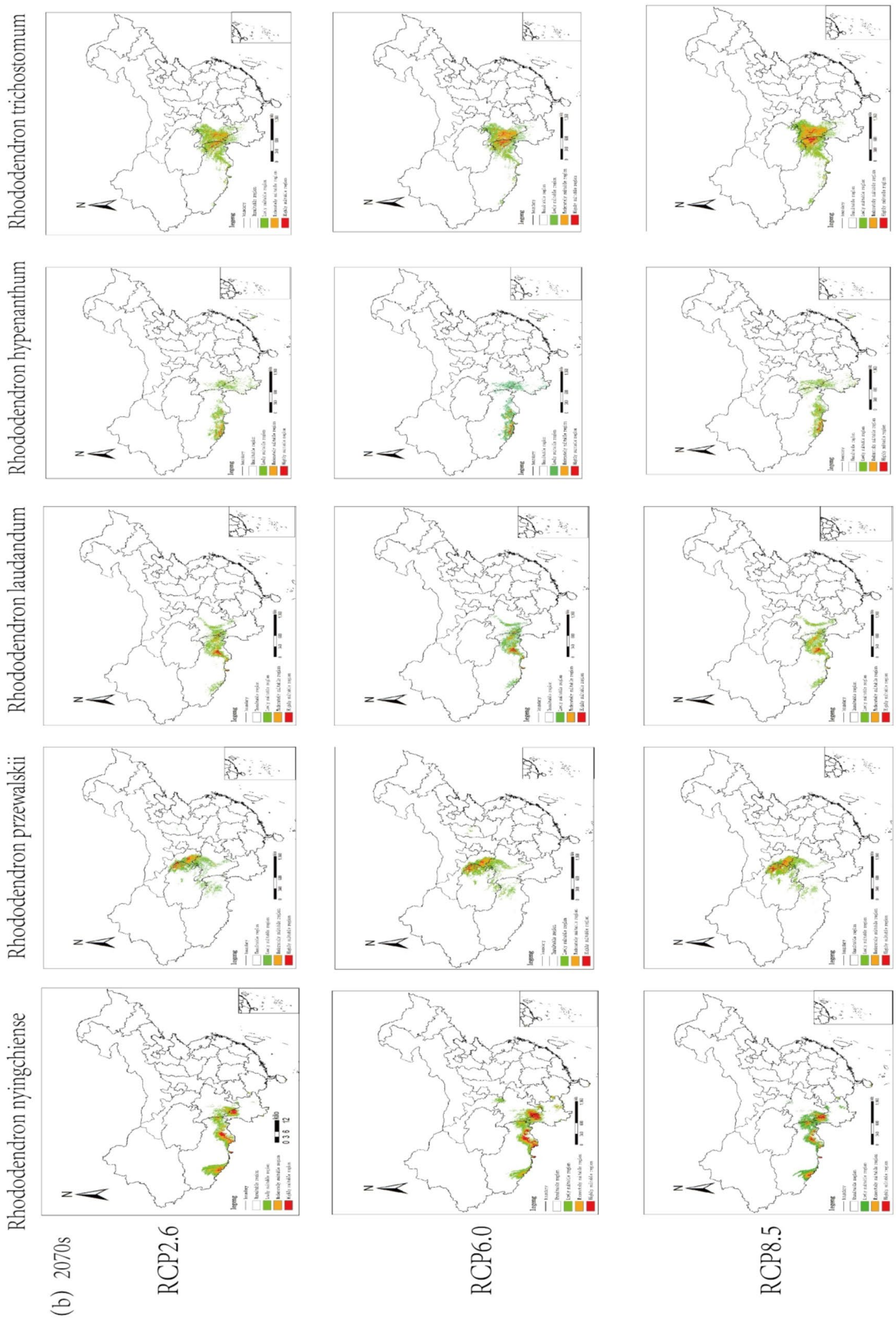

Fig. 8. (b) Prediction of the suitable range of the five species of *Rhododendron* in 2070s. RCP representative concentration pathway.

but there are also cases where suitable habitat is expanding. Habitat expansion and contraction is related to the ability of target species to adapt to environmental stresses. Yang and colleagues investigated the distribution pattern of 12 endangered medicinal plants on the Qinghai-Xizang Plateau. Their findings revealed that a quarter of these plants experienced a reduction in suitable habitat across various future scenarios. Conversely, approximately a third of the endangered medicinal plants expanded their suitable habitat due to their heightened adaptability to environmental pressures. This has resulted in a tendency for some plants living on the Qinghai-Xizang Plateau to have an elevated area of suitable habitat under future warming scenarios. Our results show that under the future warming scenario, the highly suitable area of *Rhododendron przewalskii*, *Rhododendron trichostomum*, *Rhododendron hypenanthum* as well as *Rhododendron nyingchiense* shows increasing. The area of the suitable area of *Rhododendron laudandum* shows decreasing. This shift is likely due to increasing temperatures, which have created more favorable conditions for *Rhododendrons*[34]. It is evident that the *Rhododendron* habitat has become more temperate. This study suggests that, in the context of future global warming, plants living on the Qinghai-Xizang Plateau will not always show a decrease in the size of their habitats, and that plants that are more responsive to environmental stresses may show an increase in the size of their habitats in the future[51].

Response measures and issues

The genus *Rhododendron* is the largest genus in the Rhododendron family and one of the large genera in the Chinese and Himalayan flora. There are about 960 species in the world, which are widely distributed in Europe, Asia and North America. The plants of this genus occupy an important position in horticulture and have a high ornamental value[52], the Qinghai-Xizang Plateau has already been established with a lot of different grades of national parks and nature reserves. Most of which are for the purpose of protecting the endangered wildlife. The conservation of alpine plants should also be emphasized[53]. The five *Rhododendron* species selected for this study all grow on the Qinghai-Xizang Plateau. Because alpine plants are distributed in a limited range, they are more sensitive to climate change. Many alpine plants have smaller migratory ranges and are more vulnerable to extinction in the face of global warming than their temperate counterparts[54]. This study may provide insights into the conservation of *Rhododendron* growing on the Qinghai-Xizang Plateau.

Conclusion

The spatial distribution of five species of *Rhododendron* growing on the Qinghai-Xizang Plateau was modeled under future climate change scenarios (three RCP scenarios). The key ecological niche indicators affecting their distributions were examined. Besides, the distribution of suitable habitats for *Rhododendron* was simulated for the 2050s and 2070s. Our findings suggest that:

1 Currently, the suitable habitat of *Rhododendron nyingchiense* is primarily found in the southern region of the Qinghai-Xizang Plateau. *Rhododendron laudandum* thrives in the eastern part of Xizang, while *Rhododendron hypenanthum* is predominantly located in the southern areas of Xizang. *Rhododendron przewalskii* is mainly distributed in the eastern section of the Qinghai-Xizang Plateau, covering parts of Qinghai, Gansu, and Sichuan provinces. *Rhododendron trichostomum* is predominantly found in eastern Xizang, large portions of Sichuan, and the northern area of Yunnan province.

2 Isothermality plays a crucial role in influencing the distribution of *Rhododendron* species (excluding *Rhododendron przewalskii*). Altitude emerges as the key environmental determinant for *Rhododendron przewalskii*, representing 51% importance, within the preferred range of 2700–3300 m. Altitude holds significance for *Rhododendron trichostomum*, constituting 18% weightage, within the optimal range of 3200–3900 m. This adaptation allows both *Rhododendron przewalskii* and *Rhododendron trichostomum* to thrive in high-altitude, semi-arid regions.

3 The suitable habitat for *Rhododendron przewalskii*, *Rhododendron trichostomum*, *Rhododendron hypenanthum*, and *Rhododendron nyingchiense* is expanding, while the suitable habitat for *Rhododendron laudandum* is shrinking.

Data availability

We used open- access data from the CNKI database (http://www.cnki.net/ accessed on 7 October 2022), Chi na Digital Herbarium (https://www.cvh.ac.cn/ accessed on 7 October 2022), NSII China National Herbarium Resource Leveling (http://www.nsii.org.cn/ 2017/home.php accessed on 7 October 2022), Global Biodiversity Information Facility (https://www.gbif.org/zh/), China Plant Image Library (http://ppbc.iplant.cn/ accessed on 7 October 2022).

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Author contributions
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Declarations

Competing interests
The authors declare no competing interests.

Conflict of interest
The authors declare that they have no known competing financial, interests or personal relationships that could have appeared to influence the work reported in this paper.

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