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The influence of climate change on *Primula* Sect. *Crystallophlomis* in southwest China

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Abstract

Purpose Climate change significantly affects the distribution of high-altitude plant species, particularly within the *Primula* Sect. *Crystallophlomis* found in Southwest China. This clade is valued for its ornamental and medicinal properties. This study aims to evaluate the impact of climate change on the potential distribution of *P. crystallophlomis* to inform conservation and ecological research.

Methods An optimized Maximum Entropy model (MaxEnt) was utilized to predict the suitable habitat areas of *P. crystallophlomis* under 9 scenarios, using 161 distribution records and 22 environmental variables. The model parameters were set to RM = 1.5 and FC = LQH, achieving a high prediction accuracy with an Area Under the Curve (AUC) value of 0.820.

Results The analysis identified key environmental factors influencing the suitable habitat of *P. crystallophlomis*, including annual precipitation (bio-12), temperature seasonality (bio-4), mean diurnal range (bio-2), and precipitation seasonality (bio-15). Under current climate conditions, the suitable habitats are primarily located in the eastern Qinghai-Tibet Plateau, Hengduan Mountains, and Yunnan-Guizhou Plateau, exhibiting significant fragmentation. Notable declines in potential habitat area were observed from the Last Glacial Maximum (LGM) to the Mid-Holocene (MH), with future projections indicating further reductions, particularly under the Shared Socioeconomic Pathways 585 (SSP-585) scenario.

Conclusion The suitable habitat of *P. crystallophlomis*, which tends to grow in consistently cold and moist environments, is expected to shrink, with a projected southward shift in its centroid. Global warming is anticipated to profoundly impact the suitable habitats of *P. crystallophlomis*, highlighting the urgent need for conservation efforts.

Keywords *Primula* Sect. *Crystallophlomis*, MaxEnt model, Climate change, Habitat distribution

Introduction

The increase in extreme climate events serves as a clear indicator of climate change [1, 2]. These events alter several factors, including temperature, precipitation, and carbon dioxide concentrations [3]. Such alterations have significant effects on plant growth, development, and reproduction [4, 5], ultimately leading to changes in the distribution ranges of plant species [6, 7]. The Southwest region of China is particularly vulnerable to climate change, with substantial climatic shifts documented over the past few decades, presenting formidable challenges for its distinctive alpine flora to either adapt or confront

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extinction [8, 9]. Therefore, it is essential to investigate both the current and future distribution patterns and trends of suitable habitats of species in this region for effective biodiversity conservation [10, 11].

Species distribution models (SDMs) utilize existing species occurrence data and environmental variables to estimate a species' ecological niche, reflecting its habitat preference [12]. The Maximum Entropy model (MaxEnt) is a specific type of SDM that uses the principle of maximum entropy to objectively infer unknown probability distributions from limited information [13, 14]. A key advantage of the MaxEnt model is its ability to simulate the distribution of suitable habitats using minimal occurrence data and climatic variables [15, 16]. In recent years, the MaxEnt model has gained popularity for predicting suitable habitats for various plant species. Researchers have applied this model to forecast potential suitable habitats for different species, including Saussurea [17], biodiversity conservation in Chongqing Municipality [18], and *Primula Flchnerae* [19].

Primula Sect. *Crystallophlomis* is a taxonomically and ecologically significant group within the genus *Primula* (Primulaceae) and is recognized as one of China's emblematic "Three Famous Alpine Flowers". This section comprises 38 perennial species (Table S1), which are characterized by glabrous or farinose epidermal surfaces [20]. Endemic to the alpine ecosystems of southwestern China, these species predominantly inhabit meadows and scree slopes at elevations exceeding 4,000 meters, with certain populations extending up to 5,000 meters. Their horticultural value arises from their striking floral morphology and diverse pigmentation [21]; however, their specialized adaptations to high-altitude environments pose significant challenges for ex situ conservation [22]. Reproductive success in this group is facilitated by heterostyly, a floral dimorphism that promotes cross-pollination through the spatial separation of stigmas and anthers among floral morphs. This adaptation results in outcrossing rates of 70%–85%, significantly higher than selfing rates (less than 15%), thereby enhancing genetic diversity but also creating a strong dependency on specific pollinators.

In addition to their ecological significance, certain species within this group have been traditionally used in medicine, as documented in *Sichuan Herbal Medicine* [23]. Recent phytochemical studies have identified 2-phenylchromone, a bioactive compound derived from these species, which demonstrates potent antiparasitic activity [24]. Notably, two species, *P. woonyoungiana* and *P. soongii*, are classified as Critically Endangered (CR), and an additional eight species are listed as Near Threatened (NT), representing 30% of the entire group [25]. This concerning conservation status underscores the urgent need for targeted efforts to protect these ecologically and medicinally valuable species.

This study employs distribution and climate data for *P. Crystallophlomis*, applying an optimized MaxEnt model to predict their distribution. Additionally, it identifies the key climatic factors influencing their distribution and estimates the characteristics of potential distribution regions and habitats. This study not only offers a theoretical framework for investigating resource distribution, conservation, and the artificial cultivation of *P. Crystallophlomis* but also has the potential to drive regional biodiversity conservation and foster the growth of related industries [26, 27].

Results

Optimization results and prediction accuracy

The optimal combination of characteristics (the parameter RM was 1.5, FC was LQH) was selected based on the maximum PR&AUC value (Fig. 1a). In comparison to the default model (the parameter RM was 1, FC was LQHP), the optimized model achieved an omission rate of 1.68, reflecting an improvement of 0.17. Additionally, the optimized model demonstrated robust performance, with an average AUC value of 0.820, indicating high prediction accuracy and reliability (Fig. 1b) [28].

Dominant climate factors

Employing the MaxEnt Jackknife function, the regularization gain contribution rate, in conjunction with the percentage contribution rate and importance, was utilized to discern the predominant climatic factors influencing suitable habitats [29]. The annual precipitation (bio-12), temperature seasonality (bio-4), mean diurnal temperature range (bio-2), and precipitation seasonality (bio-15) had greater impacts on potential areas that would be suitable for *P. Crystallophlomis*. The cumulative permutation importance and cumulative percentage contribution of these four environmental factors under investigation were found to be 86.6% and 73.6%, respectively (Table 1).

In the case of *P. Crystallophlomis*, annual precipitation (bio-12) is identified as the most significant determinant, accounting for 46.2% of the variation in its distribution. This finding underscores the essential role of sufficient and consistent precipitation in sustaining *P. Crystallophlomis* populations. Following this, temperature seasonality (bio-4) emerges as the second most critical factor, contributing 29.2%, thereby emphasizing the species' preference for environments characterized by minimal temperature fluctuations and stable climatic conditions.

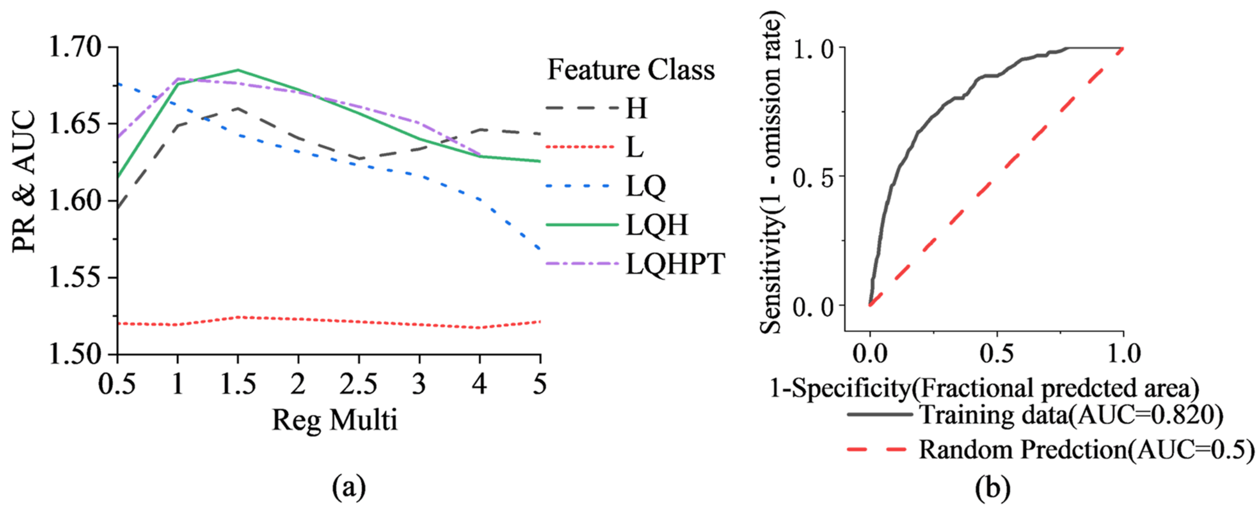

Fig. 1 Model Performance Evaluation **a** Selection of optimal model parameter combinations (weighted PR = 1 - OER); **b** AUC values of the predicted results

Table 1 Contribution rates of environmental factors in modeling

Climatic Factors	Contribution Rate (%)	Importance (%)	Threshold Range
bio-12	46.2	31.8	468–1789 mm
bio-4	29.2	19.6	442–670 ℃
bio-2	5.8	6.9	8–13 ℃
bio-15	5.4	15.3	56–178

According to the jackknife test (Fig. 2), among all single environmental variables, the mean diurnal temperature range (bio-2) and temperature seasonality (bio-4) had the higher regularized training gain. This species thrives in regions where the mean diurnal range is between 8–13 and precipitation seasonality varies from 56–97 mm (Fig. 3).

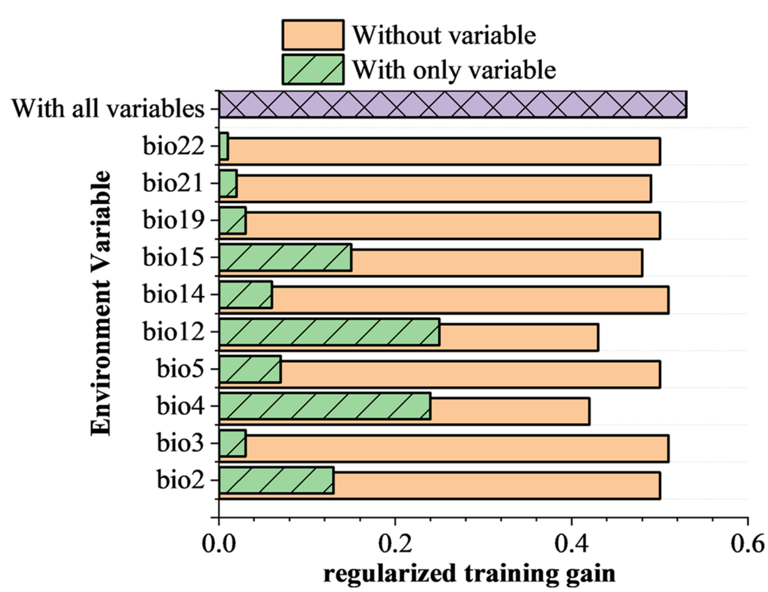

Fig. 2 Regularization gain contribution rate of Jackknife

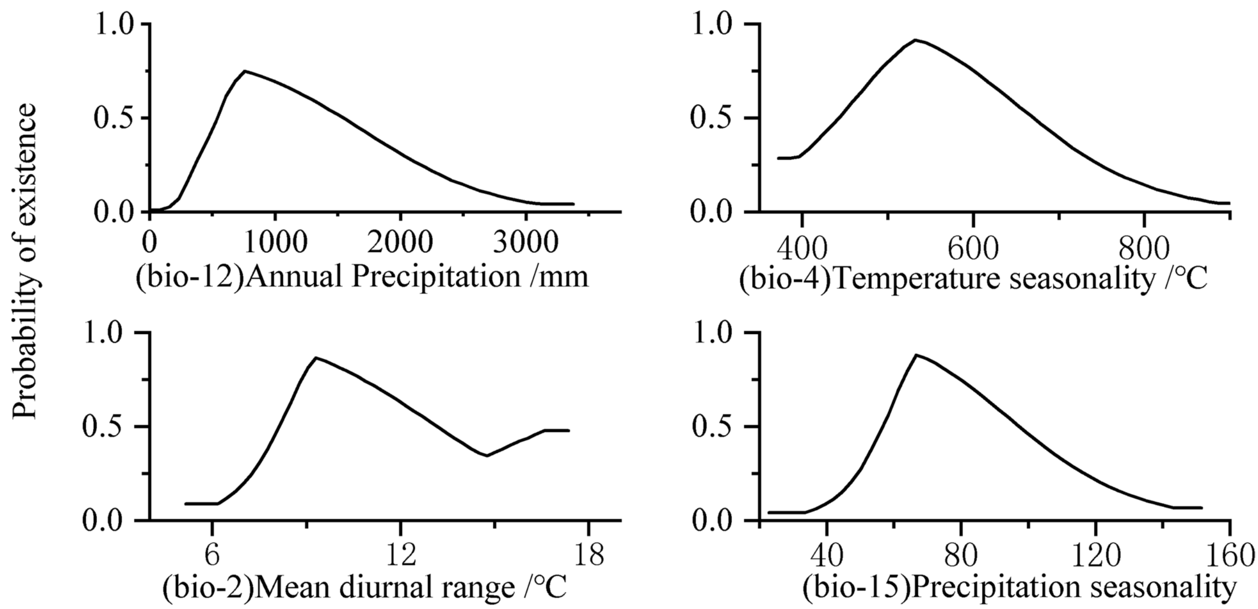

Fig. 3 Response curves of *P. Crystallophlomis*

Current distribution predictions

Under current climate conditions, the potential suitable areas for *P. Crystallophlomis* are predominantly in the southwestern region of China, encompassing Sichuan, Xizang, Yunnan, and Guizhou (Fig. 4). Specifically, *P. Crystallophlomis* occupies an area of $92.02 \times 10^4\,km^2$ in total suitable area, $27.62 \times 10^4\,km^2$ in highly suitable area, $30.92 \times 10^4\,km^2$ in moderately suitable area, and $33.47 \times 10^4\,km^2$ in generally suitable area, respectively (Fig. 4). The highly suitable regions are predominantly in the Hengduan Mountains region, the western Himalayas, as well as the Wumeng Mountains and Miaoling region in the Yunnan-Guizhou Plateau.

Historical and future distribution predictions

Historically, *P. Crystallophlomis* demonstrated a broad distribution during the Last Glacial Maximum (LGM), subsequently contracting during the Mid-Holocene (MH), and has since undergone a resurgence in the current period.

During the LGM, highly suitable areas were identified in Guizhou, eastern Yunnan, southern Sichuan, and Chongqing, encompassing a total potential suitable area of $107.52 \times 10^4\,km^2$, of which $58.76 \times 10^4\,km^2$ was classified as highly suitable. During the Mid-Holocene (MH), the total potential suitable area was reduced to $75.76 \times 10^4\,km^2$, with only $16.34 \times 10^4\,km^2$ classified as highly suitable. The highly suitable areas were confined to the Wumeng Mountains on the Yunnan-Guizhou Plateau and the northwestern Himalayas, where the species found refuge in karst formations and high-altitude ecosystems (Figure S1).

Future climate projections indicate an increase in generally suitable areas alongside a reduction in moderately and highly suitable areas (Fig. 5). Scenarios, particularly Shared Socioeconomic Pathways 585 (SSP585) for 2060 and 2080, predict a further reduction in highly suitable areas to $19 \times 10^4\,km^2$. These trends suggest that climate warming poses significant challenges to the growth of *P. Crystallophlomis*. Compared to SSP126, the SSP585 scenario forecasts a considerable decline in potential suitable areas during the same timeframe, indicating that more extreme climatic conditions will exert a greater impact.

Geographic shifts in potential suitable area

During the LGM-MH period, there was a substantial reduction of −32.65% in the potential suitable area, mainly in the Sichuan Basin and central Yunnan, where the original suitable area diminished by nearly fifty percent. Conversely, the potential suitable habitat in the Hengduan Mountains exhibited an increase. In the MH-Current period, the potential suitable area expanded by 23.22%, primarily in the southern foothills of the Daba Mountains, accompanied by sustained growth in the Hengduan Mountains region (Figure S2).

Future projections under varying emission scenarios indicate divergent regional trends. The projected suitable habitats for the year 2040 are expected to expand towards the Ridge and Valley Province of Chuandong and the southern Yunnan-Guizhou Plateau, while

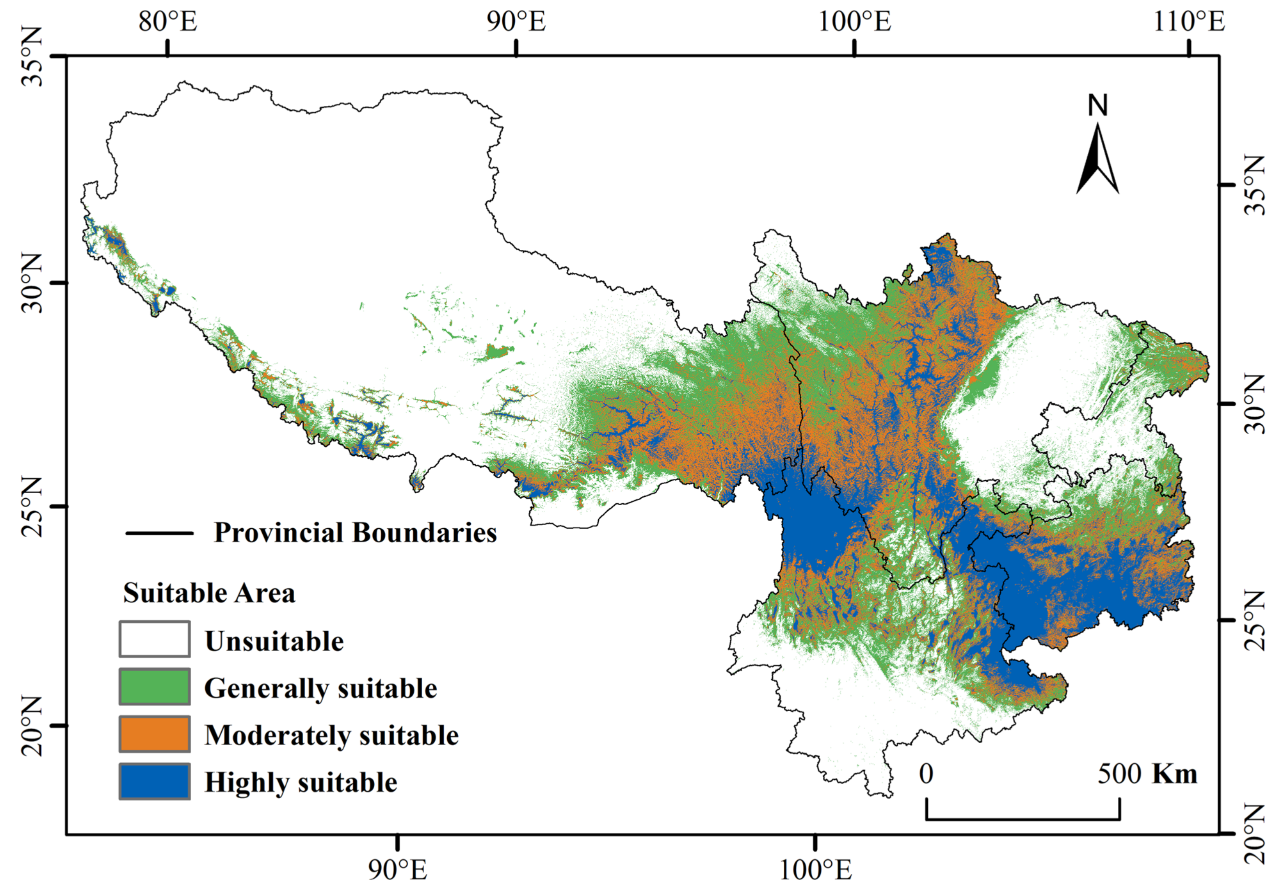

Fig. 4 Current distribution predictions for *P. Crystallophlomis*(Base map source: Ministry of Natural Resources of China, Review Number GS(2019)1822)

certain areas in the northern Hengduan Mountains are projected to undergo contraction. By 2060, the northern boundary of the overall suitable habitat is anticipated to gradually diminish, whereas the southern boundary is expected to expand. By 2080, the margins of suitable habitats are projected to persist in their decline. The SSP585 scenarios indicate a contraction of suitable habitats, and it is anticipated that forthcoming climate change may exacerbate pressures on ecosystems (Table 2).

During the LGM-MH period, the centroid of *P. Crystallophlomis* shifted northwest, while in the MH-Current period, it moved eastward. In future climate scenarios, the trend for the centroid is a southward movement, but in the SSP585-2080 period, it shifts westward. Overall, centroid movement under the SSP585 scenario is greater than under the SSP126 scenario. The longest migration distance occurred between the LGM and MH periods, with a movement of 128.5 km northwest. The shortest migration distance occurred during the SSP126-2040–2060 period, with a movement of 17 km southwest (Fig. 6).

Discussion

Environmentally dominant factors in suitable habitat of *P. Crystallophlomis*

This study utilized the MaxEnt model in conjunction with the Jackknife method to investigate the predominant climatic factors influencing *P. Crystallophlomis*. We identified the primary climatic factors influencing its suitable habitat, thereby establishing a theoretical foundation for effective utilization and conservation [30]. The identified factors included annual precipitation (bio-12), temperature seasonality (bio-4), mean diurnal range (bio-2), and precipitation seasonality (bio-15), with annual precipitation identified as the most influential factor [31, 32].

The growth and reproduction of alpine plants are constrained by temperature and resources, including soil nutrients, precipitation, and solar radiation [7, 33]. For instance, *Primula* is significantly influenced by temperature and humidity, with light having a comparatively lesser effect [34]. This study found that precipitation is the primary climatic factor limiting the distribution range of *P. Crystallophlomis*, primarily due to its impact floral trait expression and pollinator selection. Adequate

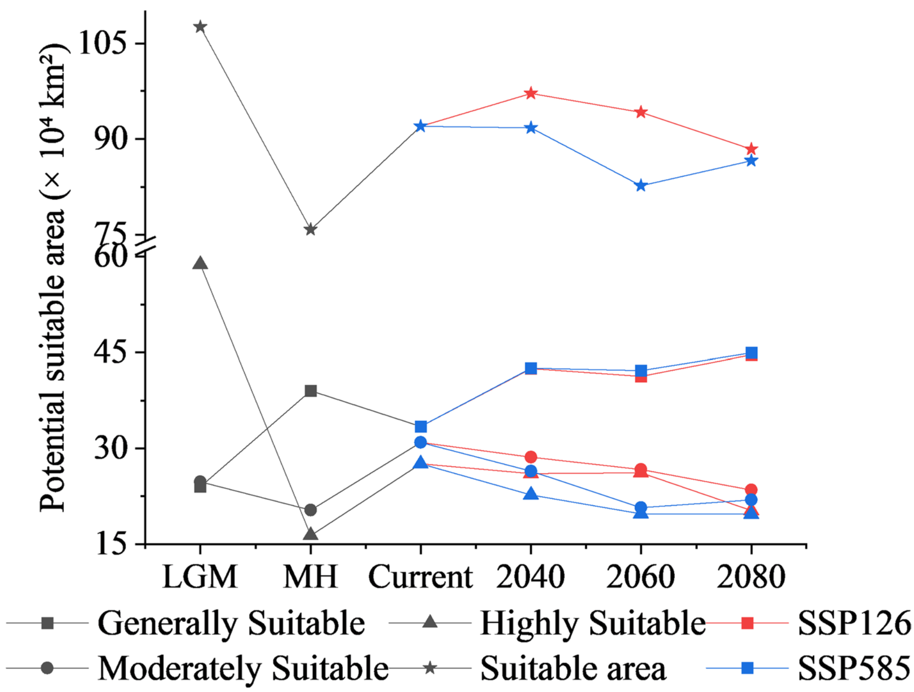

Fig. 5 Potential suitable areas of *P. Crystallophlomis* under future scenarios

Table 2 Potential suitable areas of *P. Crystallophlomis* under different climate change scenarios

Period	Area / x 10^4 km^2				Proportion of area / %			
	Expansion	Stabilized	Contraction	Change	Expansion	Stabilized	Contraction	Change
LGM-MH	17.99	54.43	53.10	−35.11	16.73	50.62	49.38	−32.65
MH-Current	26.57	66.79	8.98	17.59	35.07	88.15	11.85	23.22
Current-SSP126-2040	22.67	75.41	16.62	6.05	24.64	81.94	18.06	6.57
SSP126-2040–2060	2.61	91.42	5.72	−3.11	2.69	94.11	5.89	−3.20
SSP126-2060–2080	2.56	85.41	8.80	−6.24	2.72	90.66	9.34	−6.62
Current-SSP585-2040	19.83	68.85	19.57	0.26	22.43	77.87	22.13	0.29
SSP585-2040–2060	1.43	80.62	11.13	−9.70	1.55	87.87	12.13	−10.57
SSP585-2060–2080	9.46	77.29	5.39	4.07	11.44	93.48	6.52	4.92

moisture enhances floral growth and reproduction [35], whereas water stress in *Primula* may inhibit growth [36, 37]. When water stress exceeds 20% of fully expanded leaves, the photosynthetic rate declines significant due to stomatal closure [38].

The temperature seasonality (bio-4) and mean diurnal range (bio-2) regulate seed germination dynamics through thermal cycling effects. Experimental evidence indicates that alternating temperature regimes (e.g., 15/5 °C) can synchronize germination windows by modulating metabolic processes in *Primula* seeds [39]. Larger seasonal temperature variations (bio-4) may facilitate the breaking of physiological dormancy through cold stratification effects, particularly when combined with precipitation seasonality (bio-15). The observed dry storage-cold stratification synergy (bio-15 interaction) may enhance germination rates by 30–50% compared to constant temperature conditions [36]. These thermoperiodic mechanisms elucidate the species' adaptation to alpine environments characterized by pronounced diurnal and seasonal fluctuations.

Analysis of potential suitable areas and center of mass shifts under varied climate scenarios for *P. Crystallophlomis*

This study also employed the MaxEnt model to analyze the potential suitable habitat of *P. Crystallophlomis*,

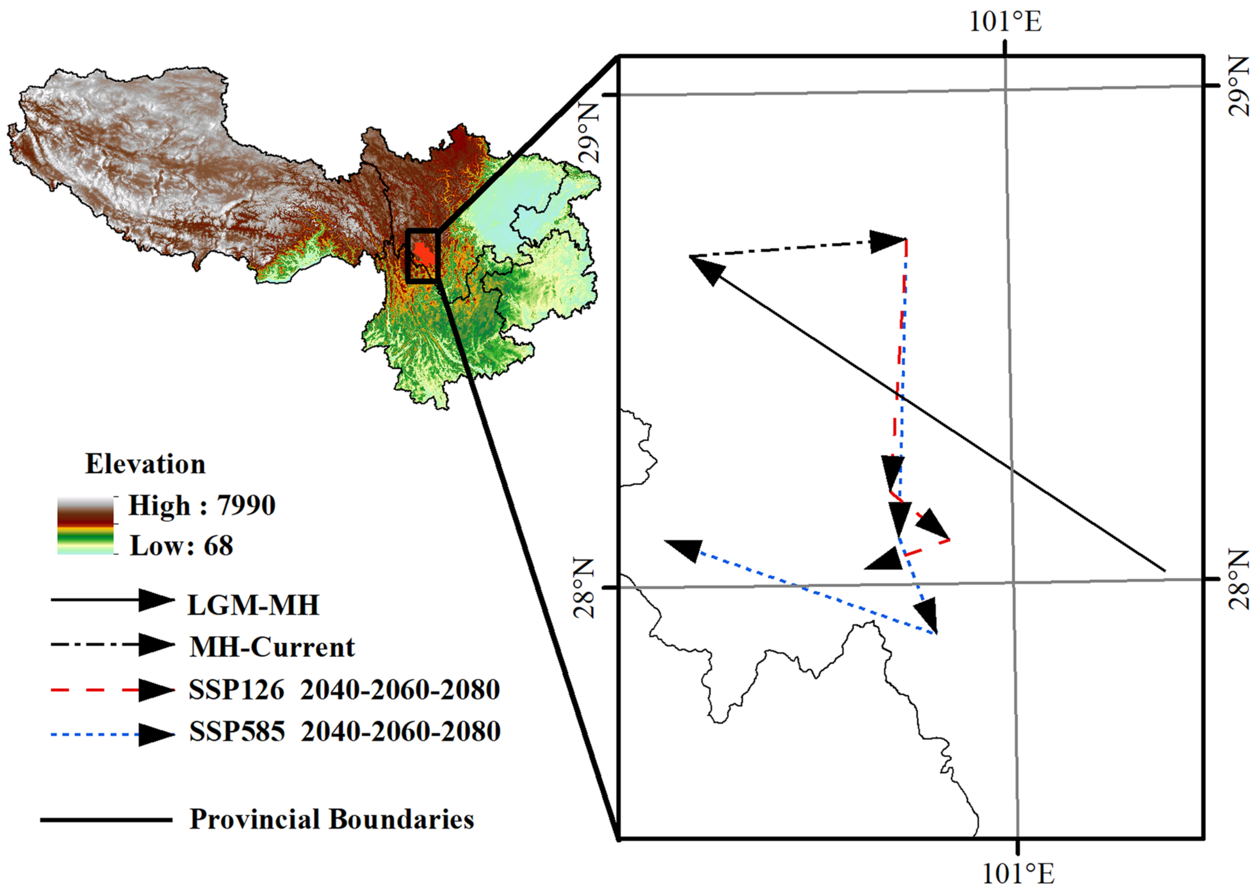

Fig. 6 Changes in the Centroids of *P. Crystallophlomis*(Base map source: Ministry of Natural Resources of China, Review Number GS(2019)1822)

revealing significant fluctuations in suitable habitats and substantial shifts in potential suitable range since the Last Glacial Maximum (LGM) [40]. Under two projected climate change scenarios, the suitable habitat area of *P. Crystallophlomis* exhibits relatively minor alterations. The potential suitable area predominantly resides in the southwestern regions of China, encompassing Sichuan, Xizang, and Yunnan, which is consistent with data compiled by Yang Guili and colleagues regarding the distribution of Chinese wild *Primula* species [41].

During the transition from the LGM to the Mid-Holocene (MH), the range of suitable habitats for *P. Crystallophlomis* experienced a significant decline, likely attributable to rapid global warming and increased seasonal variability in temperature and humidity during the MH period [42]. From the MH period to the present, the range of suitable habitats has subsequently increased, potentially associated with the uplift of the Himalayas, which obstructs warm and humid airflow from the Indian Ocean, resulting in a colder and drier Hengduan Mountain region [43]. Owing to the unique biological and physiological adaptations of *P. Crystallophlomis* , their impact remains relatively minimal, even under harsh alpine climatic conditions [44]. The climate scenario SSP5-8.5 exerts a more pronounced impact on *P. Crystallophlomis* compared to the SSP1-2.6 scenario, as *P. Crystallophlomis* predominantly inhabits alpine regions that necessitate a cool environment for optimal growth and development [45, 46]. Under the SSP5-8.5 scenario, substantial global temperature increases are anticipated to exert a more profound influence on *P. Crystallophlomis* [47].

Predictions suggest that under future climate warming scenarios, plant species are anticipated to migrate toward higher altitudes or latitudes [48]. However, the center of distribution for *P. Crystallophlomis* populations has predominantly shifted northwards in the past and is projected to shift southwards in the future [49]. Studies investigating the transcriptomic changes of *Primula obconica* at various stages suggest that it adapts more readily to heat stress than to cold stress [50], which may drive its movement towards lower altitudes and latitudes [51].

Suggestions and potential limitations

The MaxEnt model is well-regarded among species distribution models for its accuracy and stability [27]. However, this study has several limitations that must be acknowledged. First, the model does not account for the potential adaptive evolution of the species in response to climate change. Second, interspecific interactions, particularly pollinator dynamics and competitive relationships, were not included. Third, anthropogenic influences such as grazing pressure and habitat management, were not considered. Finally, uncertainties in climate projections, particularly under extreme scenarios such as SSP585, may affect model accuracy.

To address these limitations and enhance conservation effectiveness, specific recommendations are proposed. Population management should prioritize the protection of populations with more than 500 flowering individuals to maintain genetic diversity and reproductive success, complemented by monitoring programs to track demographic changes [52]. Systematic surveys of pollinator communities, particularly bees and moths, should be conducted to identify key species and enhance their habitats through targeted conservation measures [53]. Ex-situ conservation strategies should be developed through seed banks with a minimum storage duration of 5 years, incorporating regular viability testing and backup collections. Habitat protection measures should be enforced during critical reproductive periods, including flowering and seed maturation stages, with grazing control and prohibition of plant collection in key habitats. Restoration strategies should consider cluster planting designs to enhance floral density and improve pollination efficiency in degraded habitats, along with long-term ecological studies to monitor effectiveness.

These conservation actions should be integrated with ongoing research efforts to refine species distribution models and improve our understanding of *P. Crystallophlomis* ecology. Future studies should incorporate additional environmental variables and validate model predictions using alternative approaches such as Random Forest (RF), Generalized Linear Models (GLM), and Genetic Algorithms for Rule Set Prediction (GARP).

Materials and methods

Acquisition and processing of distribution data

The geographic distribution data for *P. Crystallophlomis* in Southwest China were compiled from two primary sources: (1) the Global Biodiversity Information Facility (GBIF, http://www.gbif.org), contributing 96% of the total records; and (2) herbarium specimens archived at the Kunming Institute of Botany, Chinese Academy of Sciences (KUN) [54]. The initial dataset comprised 1,008 occurrence points, encompassing all 38 species across five provinces: Sichuan, Yunnan, Xizang, Guizhou, and Chongqing.

To mitigate spatial sampling bias and potential geolocation errors, we implemented a spatial thinning protocol using the SDMToolbox [55], specifically the "Spatially Rarefy Occurrence Data for SDMs" tool. This procedure retained only one occurrence point per 10 km × 10 km grid cell. After filtering, 161 high-confidence distribution points were retained, predominantly clustered in Sichuan, Yunnan, and Xizang (Fig. 7). This approach balances spatial resolution with ecological realism, a critical consideration for alpine species, that are highly sensitive to topographic and climatic gradients. Subsequently, a Minimum Convex Polygon (MCP) was generated from the refined occurrence data, with a 10 km buffer applied to account for potential sampling biases and microhabitat heterogeneity.

Environmental data

The environmental variables included 19 bioclimatic parameters (bio1–bio19) from WorldClim (https://www.worldclim.org/data/index.html) and three topographic derivatives (elevation, slope and aspect) derived from the WorldClim Digital Elevation Model (DEM) using ArcGIS. Contemporary climate data (1970–2000 baseline) were obtained from WorldClim 2.1 [56], while future climate projections for 2040, 2060, and 2080 under SSP1-2.6 and SSP5-8.5 scenarios were based on the BCC-CSM2-MR model within the CMIP6 framework [57, 58]. Historical climate layers for the Last Glacial Maximum (LGM) and Mid-Holocene (MH) were sourced from CHELSA [59] and WorldClim 1.4, respectively, then resampled to a uniform resolution of 30 arc-seconds. Before being input into the model, the bioclimatic variables (bio1, bio2, bio4–bio11) from historical periods were rescaled by a factor of 0.1 to restore their original measurement scales, ensuring cross-era comparability.

To quantify the species' growing-season thermal and hydric requirements while minimizing multicollinearity, we implemented a two-stage variable selection protocol. First, Pearson correlation analysis (threshold: ($r < 0.8$)) was conducted to identify and remove highly correlated variables. Second, based on contribution rates derived from preliminary MaxEnt modeling, factors exhibiting both high collinearity and low contribution rates were excluded [60]. Through this iterative refinement process, 10 variables were selected for final modeling: bio2 (mean diurnal range), bio3 (isothermality), bio4 (temperature seasonality), bio5 (maximum temperature of the warmest month), bio12 (annual precipitation), bio14 (precipitation of the driest month), bio15 (precipitation seasonality), bio19 (precipitation of the coldest quarter), bio21 (slope), and bio22 (aspect) (Fig. 8). All layers were

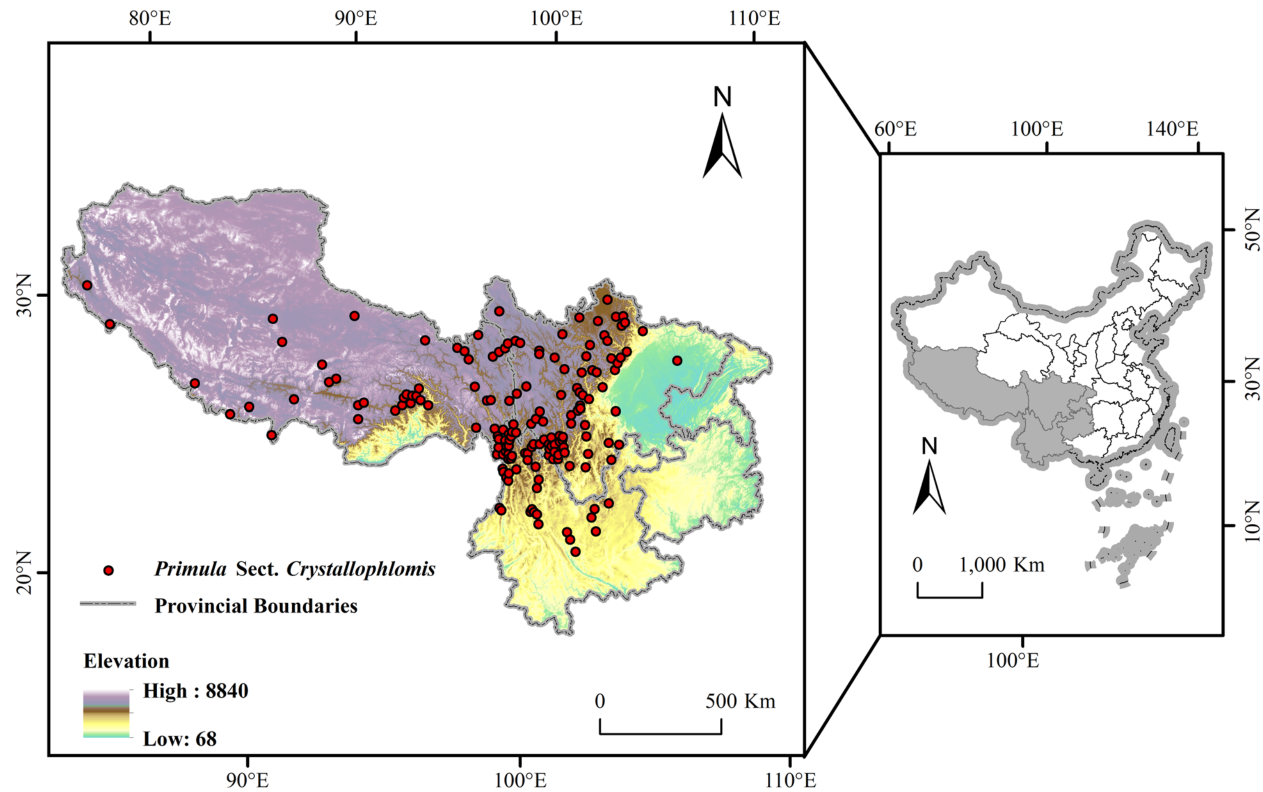

Fig. 7 Distribution of *P. Crystallophlomis* in the southwest region(Base map source: Ministry of Natural Resources of China, Review Number GS(2019)1822)

clipped to the study region (Southwest China), reprojected to the WGS84 coordinate system, and converted to ASCII format for model compatibility. Spatial resolution consistency was verified across datasets using SDMTools [55].

Model optimization and prediction methods

The SDMTools toolbox was implemented in ArcGIS 10.8.1, utilizing the "Run MaxEnt: Spatially Jackknife" tool. This process involved preparing distribution data and environmental layers, selecting output response curves in logistic format, and saving results in .asc format. MaxEnt version 3.4.4 [61] was employed, with 25% of occurrence points allocated to the test set and 75% to the training set. The model was run 10 times with a maximum of 500 iterations per run, and minimum training presence thresholds were included to calculate omission rates. We tested 40 combinations of feature classes (FC) and regularization multipliers (RM), including FC types (L, LQ, H, LQH, LQHPT) and RM values (0.5, 1, 1.5, 2, 2.5, 3, 4 and 5). Model selection followed a three-step protocol: (1) prioritize models with the lowest omission rate (OR), (2) among low-OR candidates, select those with the highest AUC values, and (3) choose the simplest feature class configuration when multiple models exhibited similar performance. This optimization identified the best-performing parameters. Finally, output files were processed, and all models were executed automatically using batch files, with the optimal model selected to generate the final results.

The accuracy of the MaxEnt model results was evaluated using the Receiver Operating Characteristic (ROC) curve and the area under the curve (AUC). The omission rate (OR) was employed to assess model optimization and predictive precision [62]. AUC values are interpreted as follows: AUC 0.50 indicates that the model' discriminative ability is no better than random chance; an AUC between 0.50 and 0.80 is considered "fair"; an AUC between 0.80 and 0.90 is "good"; and an AUC between 0.90 and 1.00 is "excellent" [63].

The output files from the software were converted into raster data using ArcGIS, and the prediction results for the suitable habitat areas of *P. Crystallophlomis* were reclassified. Based on the maximum training sensitivity plus specificity, the suitable habitat areas were categorized into non-suitable zones (0–0.3), low suitability zones (0.3–0.5), medium suitability zones (0.5–0.7), and high suitability zones (0.7–1) [64, 65]. The area

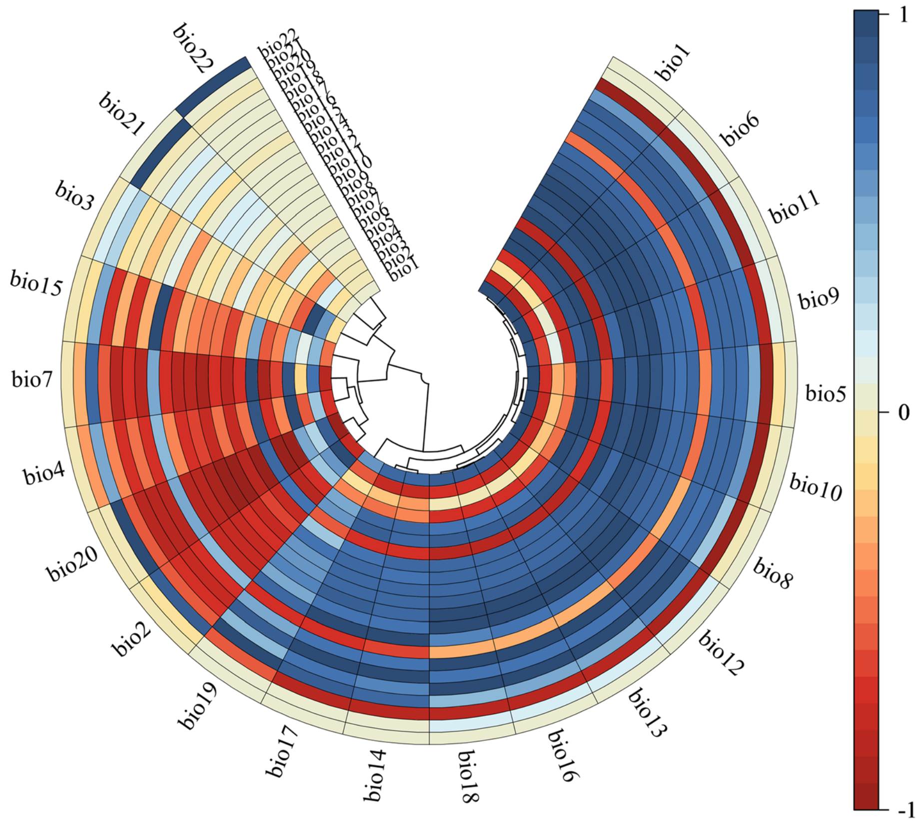

Fig. 8 Correlation of environmental factors

calculation was based on the number of suitable pixels obtained from the software, multiplying the pixel count by the pixel area to derive the statistical area. However, actual pixels may be divided by boundary lines, leading to potential accuracy errors in the calculation.

Furthermore, the results were divided into non-suitable and suitable zones, using the low suitability zone as the threshold. Potential habitat changes and centroid shifts were subsequently analyzed utilizing SDMTools, and figures were created using Origin 2024b.

Conclusion

In this study, we utilized the MaxEnt model with optimized parameters for the first time to predict the distribution of potential habitats for *P. Crystallophlomis*, considering both current climatic conditions and anticipated climate change. Under the current climate scenario, the areas classified as highly suitable, moderately suitable, and poorly suitable accounted for 27.62×10^4 km^2, 30.92×10^4 km^2, and 33.47×10^4 km^2, respectively. The species is primarily distributed across Sichuan, Xizang, Yunnan, and Guizhou.

Our findings indicate that future climate change is likely to substantially reduce the area of highly suitable habitats for *P. Crystallophlomis*. The most significant environmental factors influencing the habitat of *P. Crystallophlomis* have been identified as annual precipitation (Bio12) and temperature seasonality (Bio4). Global warming may lead to further contraction and a southward shift of the potential habitat for *P. Crystallophlomis* in southwest China. Based on these findings, it is recommended that efforts be strengthened to collect and preserve wild germplasm resources of *P. Crystallophlomis* in habitats at risk of extinction. This study also serves as a reference for the collection, preservation, and medicinal and ornamental applications of wild relatives of *Primula*.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12870-025-06466-1.

Additional file 1: Table S1 the 38 species within *P. Crystallophlomis*.

Additional file 2: Figure S1 Potential suitable areas of *P. Crystallophlomis* under different scenarios.

Additional file 3: Figure S2 Spatial variation in potential habitat of *P. Crystallophlomis* under various climate scenarios compared to the previous climate scenario.

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Authors' contributions
Donglai HUA, Zhixi FU, Lijun Zhu, Ling LIconceived this study. Hang ZHOU, Ao LI, Xuequn LUO, Zhixi FU, Jiafeng WANG, Jiaxing TIAN conducted the acquisition, analysis, or interpretation of data. Ao LI, Gan XIE, Hang ZHOU created new software used in the work. Ao LI, Gan XIE, Donglai HUA drafted the work or substantively revised it. All authors read and approved the final manuscript.

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Data availability
All links to the input data are reported in the manuscript, and all the output data are available upon request to the authors.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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