Predicting the Implications of Climatic Alterations on the Distribution of Endangered Species: A Case Study of Saxifragaceae on the Qinghai-Tibet Plateau

Chenglin Sun
Qinghai Normal University
Wenpeng Chen
Qinghai Normal University
Yuping Liu
Qinghai Normal University
Tao Liu
Qinghai Normal University
Xu Su
xusu8527972@126.com

Qinghai Normal University
Yonghui Zhou
Ganzhou Research Institute of Vegetables and Flowers
Dong Wang
Qinghai Normal University
Xiaoli Li
Qinghai Normal University
Xiaoyan Ma
Qinghai Normal University
Chengrong Wei
Qinghai Normal University
Shengtao Wang
Qinghai Normal University
Nima Suonan
Qinghai Normal University
Mir Muhammad Nizamani
Guizhou University

Article

Keywords: Climate change, Saxifragaceae, Maximum entropy model, Climatic scenario, Potential distribution, Shared socioeconomic pathway

Posted Date: April 18th, 2024

DOI: https://doi.org/10.21203/rs.3.rs-4128394/v1

Additional Declarations: No competing interests reported.

Abstract

Understanding the potential effects of climate change on species distribution is vital for the conservation of endangered taxa. The Saxifragaceae family, known to be susceptible to habitat disturbance, has a diverse distribution. While a significant portion is found on the Qinghai-Tibet Plateau (QTP), about half the species of Saxifraga are native to Europe, and other genera, such as Heuchera, have their centers of diversity in regions like North America and Japan. In this study, we employ the Maximum Entropy (MaxEnt) model in conjunction with Shared Socioeconomic Pathways (SSPs) to assess the potential influence of climate change on the distribution and richness of four endangered Saxifragaceae species (Saxifraga cernua L., Saxifraga tangutica Engl., Saxifraga przewalskii Engl. ex-Maxim., Saxifraga unguiculata Engl.) on the QTP, spanning time periods from the Last Glacial Maximum to 2080. Our results indicate that factors such as elevation, slope, mean annual temperature, isothermality, precipitation seasonality, and precipitation during the wettest quarter significantly affect species distribution patterns. Historical climate models demonstrate that approximately 30% of the QTP provided highly suitable habitat for Saxifragaceae species. Current projections suggest that this proportion has increased to over 30% and is anticipated to remain above 30% for the subsequent three-time intervals. Optimal habitats have been identified in southeastern QTP, western Sichuan, and northern Yunnan. The taxa are predicted to shift southward in response to future climate changes. Our findings underscore the importance of implementing conservation strategies that prioritize the establishment of protected areas in the southeastern QTP to safeguard these vulnerable Saxifragaceae species.

Introduction

Climate change's potential implications for biodiversity and ecosystem functioning are of paramount concern, especially as the globe braces for more pronounced shifts in weather patterns and temperatures[1,2]. One critical area affected by climate change is species distribution, especially within habitats already susceptible to environmental alteration[3]. The Qinghai-Tibet Plateau (QTP) stands as a salient example of such habitats, harboring ten thousand species uniquely adapted to its climatic and geographical intricacies.

The Saxifragaceae family, a diverse assemblage of flowering plants, finds a significant portion of its distribution within the QTP. Comprising around 10 tribes, 41 genera, and over 750 species, this family predominantly thrives in temperate zones[4]. Most notable is the *Saxifraga* genus, representing the bulk of the family, which features around 450-500 species that are prevalent in the mountainous terrains of Europe and Asia, with notable presence in the Arctic region[5]. Within China, specifically in the QTP region, an impressive count of approximately 220 *Saxifraga* species has been documented[6]. Despite their extensive distribution, there's a striking knowledge gap surrounding the environmental determinants shaping their habitat preferences.

Endemic species, such as those within the Saxifragaceae family found in the QTP, serve as the ecosystem's backbone, fostering biodiversity and providing invaluable ecological services[7]. However, with climate shifts come inherent challenges, notably the fragmentation of suitable habitats and the looming threat of invasive species competition[8]. For plateau dwelling species, the stakes are even higher, given their limited populations and specialized evolutionary adaptations[9,10]. Consequently, any disturbance in their habitats might instigate a domino effect, compromising ecosystem health, which in turn supports life on our planet.

Given the urgency and gravity of these climate-induced changes, harnessing predictive tools like Species Distribution Models (SDMs) has become indispensable. Among these, the Maximum Entropy (MaxEnt) model is hailed for its proficiency in ecological and biogeographical predictions, even with minimal data sets. It also has disadvantages, for example, due to the relationship between the number of constraint functions and the number of samples, the calculation of iterative process is huge and the practical application is difficult. The primary aim of this study is to utilize the MaxEnt model to comprehensively understand how four species within the Saxifragaceae family have been, are currently, and will likely be distributed across the QTP. The focus is to unravel the complex relationships between different environmental factors-namely elevation, slope, aspect, and various abiotic variables-and how these elements influence the distribution of these species in different climatic conditions. By integrating climatic data and environmental determinants, the study seeks to shed light on the intricate dynamics that govern the habitat preferences and survival of these plants under varying climate scenarios, both in the past and looking into the future.

In pursuit of this, our study is steered by two principal questions: (1) Which environmental variables predominantly shape the distribution of Saxifragaceae species? (2) How the distribution will change? Through this endeavor, we aspire to illuminate pathways for effective conservation strategies, ensuring that the unique Saxifragaceae species of the QTP endure the test of time and change.

Study area

The Qinghai-Tibet Plateau, also known as the "roof of the world" and the "third pole" of the earth, is China's largest and highest plateau. It stretches from the southern margin of the Himalayas in the south to the northern margin of the Kunlun, Altun, and Qilian Mountains in the north. Additionally, it stretches from the Pamir Plateau and Karakoram Mountains in the west to the Qinling Mountains in the east and the Loess Plateau in the northeast. With an average elevation exceeding 4000 m above sea level, the QTP is located between 73°19’~104°47’E and 26°00’~39°47’N.

The QTP has an area of 2.5724×10^6 km^2 and is situated in the south-central part of the Eurasian continent. It is about 2,946 km long from east to west and about 1,532 km wide from south to north, accounting for 26.80% of the total land area of China[11]. The QTP exhibits a significant variation in elevation, with high elevations in the west and lower elevations in the east. The cold climate, dryness, and harsh natural conditions significantly influence plant distribution patterns. The unique geographical features and surface characteristics of the QTP have created a highly complex climate[12].

The QTP undergoes a climatic transition from warm-wet to cold-dry from southeast to northwest[13]. There are distinct seasonal and regional differences in annual precipitation, primarily in summer. However, the southern QTP receives the most precipitation in spring and fall. In the context of global warming, the QTP is experiencing significant climatic changes, making it an ideal area for studying the effects of global warming on the alpine plant system[14].

Materials And Methods

Study species

The materials for this study were obtained from four representative species of Saxifragaceae in the alpine meadow of the QTP, namely, *Saxifraga cernua*, *S. przewalskii*, *S. tangutica*, and *S. unguiculata*. The geographic location information for these four species was obtained from six sources: (1) Distribution point data collected by the research group through field investigations; (2) Global Biodiversity Information Facility (GBIF, https://www.gbif.org/); (3) China Digital Herbarium (CVH, http://www.cvh.ac.cn/) search data; (4) National Specimen Sharing Platform data (NSII, http://www.nsii.org.cn/); (5) Teaching Specimen Resource sharing platform (MNH, http://mnh.scu.edu.cn/) data; and (6) literatures on the distribution of the target species.

The collected data were processed using ArcGIS 10.8, where duplicate species distribution records were eliminated. For the species *Saxifraga cernua*, there were originally 55 records. After removing 14 duplicate records, 41 records remained for modeling. For *Saxifraga unguiculata*, there were initially 84 records. With 15 duplicates removed, the number of records available for modeling is 69. In the case of *Saxifraga tangutica*, there were 115 original records. Once 27 duplicates were taken out, 88 records were left for modeling. Lastly, for *Saxifraga przewalskii*, out of 43 original records, 12 duplicates were removed, leaving 69 records for the modeling process. In order to reduce the impact of spatial autocorrelation of sample points on niche model construction caused by the occurrence of too many repeated points in the same grid, ENM Tools software was used in this study to screen and eliminate species distribution points with high spatial autocorrelation, and finally retain geographical distribution points for subsequent processing. The remaining records were exported to Excel and converted to “CSV” format for prediction purposes in the MaxEnt model (Figure 1).

Figure 1 Location point map of four Saxifragaceae species.

Environmental variables

Environmental variables play a crucial role in shaping the species distribution, the selection of environmental variables has an important effect on the distribution of species. Based on the actual distribution information of species and environmental variables, the unknown probability distribution of species is inferred, and then the potential distribution of target species is obtained. To assess the impact of environmental variables on the distribution of Saxifragaceae species on the QTP, we followed the standard procedure provided by Zurell et al[15]. First, we identified potential environmental variables using a literature review and expert consultation. We considered variables such as temperature, precipitation, and elevation.

This study utilized 19 bioclimatic and three topographical variables as initial environmental factors. The bioclimate variables were obtained from the WorldClim-Global Climate dataset (http://www.worldclim2.0.org/) and downloaded[16]. The dataset provides information on 19 climatic variables, each with a geographical precision of 30 seconds, related to precipitation and temperature from 1970 to 2000. These data served as the basis for the Climate Scenario. EarthEnv (https://www.earthenv.org) was used to determine several aspects of the topography of the QTP within the geographical space, including elevation, slope, and aspect.

For future bioclimate data, this study utilized the shared socioeconomic pathways (SSPs) scenarios, which contain four scenarios with a geographical resolution of 30 seconds. The potential geographic distribution was predicted using climate variable data under the medium SSP245 shared socioeconomic path scenario.

All environmental variables, including climate and topography, were resampled using ArcGIS 10.8 to a spatial resolution of one kilometer and processed in the same geographical range. To avoid collinearity and ensure model accuracy, correlation coefficients among variables were calculated using general accounting, and variables with correlation coefficients less than 0.8 were selected for modeling[17]. Finally, nine environmental variables were modeled for further analysis (Table 1).

Table 1 Environmental variables selected in the MaxEnt model.

Data source	Variable category	Variable name	Abbreviation	Unit
WorldClim	Climate	Annual Mean Temperature	Bio1	°C
		Mean Diurnal Range (Mean of Monthly (max temp-min temp)	Bio2	°C
		Isothermality (BIO2/BIO7) (×100)	Bio3	°C
		Temperature Annual Range (BIO5-BIO6)	Bio7	°C
		Precipitation Seasonality (Coefficient of Variation)	Bio15	mm
		Precipitation of Wettest Quarter	Bio16	mm
EarthEnv	Topographic	Elevation	Ele	m
		Slope	Slo	°
		Aspect	Asp	°

Next, we selected candidate variables using a filtering approach based on a correlation matrix and variance inflation factor (VIF) analysis. We removed highly correlated variables ($|r| > 0.5$) and those with a VIF > 10 to reduce multicollinearity. We then used a model selection process based on Akaike's information criterion (AIC) to identify the most critical environmental variables for predicting the distribution of Saxifragaceae species. We constructed candidate models using a combination of the selected environmental variables and selected the model with the lowest AIC as the best model. Finally, we evaluated the contribution of each environmental variable to the model using variable importance measures such as permutation importance or relative contribution. This allowed us to identify the most critical environmental variables for the species distribution of Saxifragaceae and to understand their relative importance in shaping the distribution patterns. By following this standard procedure, we ensured a rigorous and systematic approach to identifying and selecting environmental variables for our study of Saxifragaceae species on the QTP.

MaxEnt model processing

The MaxEnt model was employed to forecast the potential distribution of Saxifragaceae species based on their current geographic locations and associated environmental variables. The model generated a spatial representation of habitat suitability on a scale that ranged from 0 to 1 (least to most suitable)[18].

MaxEnt model is based on the principle of maximum entropy, that is, the model with the maximum entropy is selected when the known conditions are met. It uses the existing distribution points and environmental variables of species to calculate the ecological needs of species and simulate the potential distribution of species. We utilized MaxEnt 3.4.4 to input the data, importing the species data of Saxifragaceae and nine environmental variables. All other parameters were maintained at their default values (500 iterations, 0.00001 convergence threshold, and 10,000 maximum background points)[19]. The jackknife method was employed to determine the most significant environmental factors[20]. For model training, 70% of known distribution points were randomly selected, and the remaining 30% were reserved for testing[21].

We used the area under the receiver operating characteristics curve (AUC) to assess the model's accuracy, with values ranging from 0 to 1. AUC values between 0.7 and 0.8 are classified as “fair”, those between 0.8 and 0.9 are classified as “good”, and those above 0.9 are classified as “outstanding”. Typically, acceptable AUC values average greater than 0.75[19,22].

Analysis of model predictions

The model outputs were converted from raster to vector using ArcGIS 10.8 and classified into four arbitrary habitat appropriateness groups based on natural breaks[23]. The zonal statistics tool was then used to calculate the unsuitable, low-suitability, moderate-suitability, and highly-suitable areas[24]. To convert each species' continuous habitat suitability values into a binary environment with a threshold of 0.1. A four-level grading system was established to indicate the trend of the species richness of Saxifragaceae based on the suitability value, which ranged from (0-0.1, 0.1-0.3, 0.3-0.5, and 0.8-1.0), respectively. Among them, 0-0.1 represents unsuitable areas, 0.1-0.3 represents low suitability areas, 0.3-0.5 represents moderately suitable areas, and 0.8-1.0 represents highly suitable areas.

Results

Model accuracy and the contribution of environmental factors

In order to avoid overfitting of prediction results, we eliminated environmental variables with correlation coefficients greater than 0.8 through correlation analysis. According to the model simulation results, it is found that the mean AUC values obtained from model testing with present and future climatic scenarios were above 0.85. The average AUC values from model training were above 0.9, indicating good to excellent model performance. An internal jackknife test was conducted to determine the relative importance of various environmental factors. The results revealed that the distribution of the four species of Saxifragaceae on the QTP was influenced by topography, specifically elevation (The contribution rate is more than 50%), climate variables such as annual mean temperature, isothermality (Bio2/Bio7) (×100), precipitation seasonality, and precipitation during the wettest quarter, as well as other factors (Table 2).

Table 2 The contribution (%) of environmental variables to the MaxEnt model output of four species of Saxifragaceae.

Species name	Elevation	Slope	Bio1	Bio3	Bio15	Bio16
Saxifraga cernua	74.1	3.0	5.2	2.7	0.7	2.7
Saxifraga tangutica	60.7	0.5	1.3	8.3	5.2	10.1
Saxifraga przewalskii	62.8	0.8	0.1	0.0	4.7	21.9
Saxifraga unguiculata	57.7	1.9	0.0	1.7	18.8	5.6

The elevation of the habitats suitable for the growth of Saxifragaceae species was identified as the most crucial determinant of their distribution range. Among the four species, elevation contributed to over 50% of the model's outcomes. The independent variables used to determine the distribution of the four species of Saxifragaceae included the slope (Slo: average of 2.02%), annual mean temperature (Bio1: average of 1.36%), isothermality (BIO2/BIO7) (100) (Bio3: average of 2.86%), precipitation seasonality (Bio15: average of 6.12%), and precipitation during the wettest quarter (Bio16: average of 8.74%).

Potential distribution of four species from Saxifragaceae under climatic conditions at different periods

S. cernua is predominantly distributed in the southwest and southeast regions of the QTP, with the highest proportion of the high-suitability area and an observed shift towards the southeast (Figure 2-5). The suitable high regions of *P. trinervis*, *S. unguiculata*, and *S. tangutica* are located in the southeastern portion of the QTP. Meanwhile, *S. przewalskii* displays high suitable areas in the northeast of the plateau, with a suitable middle area located in the southeast.

As shown in Figure 2-5, the high-suitability area has gradually decreased and become relatively scattered from the last glacial age to the present. In contrast, from the present to the subsequent three time periods, the high-suitability area is predicted to increase and become concentrated within its distribution range gradually.

Figure 2 The change of distribution pattern of *Saxifraga cernua*. A: stand for last glacial maximum; B: stand for middle Holocene; C: stand for 1970-2000; D: stand for 2021-2040; E: stand for 2041-2060; F: stand for 2061-2080.

Figure 3 The change of distribution pattern of *Saxifraga tangutica*. A: stand for last glacial maximum; B: stand for middle Holocene; C: stand for 1970-2000; D: stand for 2021-2040; E: stand for 2041-2060; F: stand for 2061-2080.

Figure 4 The change of distribution pattern of *Saxifraga przewalskii*. A: stand for last glacial maximum; B: stand for middle Holocene; C: stand for 1970-2000; D: stand for 2021-2040; E: stand for 2041-2060; F: stand for 2061-2080.

Figure 5 The change of distribution pattern of *Saxifraga unguiculata*. A: stand for last glacial maximum; B: stand for middle Holocene; C: stand for 1970-2000; D: stand for 2021-2040; E: stand for 2041-2060; F: stand for 2061-2080.

Figure 6 Changes of suitable area of Saxifragaceae species.

Changes in the potential distribution area

The potential distribution area of the highly suitable species of Saxifragaceae is 1,431 km^2 (1.7% of the QTP), primarily distributed in the southeastern region of the plateau, as depicted in Figure 2-5, under past, current, and future climate scenarios. Additionally, the combined potential distribution area of the four species from Saxifragaceae is 4,740.5 km^2 (5.2% of the QTP) under these scenarios. The potential distribution area of Saxifragaceae species generally decreases with increasing abundance under different climate scenarios, as indicated in Table 3 (Figure 6).

Over time, the unsuitable areas for the four species of Saxifragaceae have continuously decreased, whereas the highly-suitable regions have increased. Among the species, the unsuitable areas for *S. tangutica*, *S. przewalskii*, and *S. unguiculata* accounted for 50% of the total area of the QTP under different climatic backgrounds.

During the last glacial maximum, the largest suitable height area was for *S. cernua* (73.46 km^2, accounting for 29.4% of the QTP), while the smallest was for *S. tangutica* (29.06 km^2, accounting for 11.6% of the QTP). The largest area during the middle Holocene was for *P. trinervis*; during the period (1970-2000), it was for *S. tangutica*. In the subsequent three periods (2021-2040, 2041-2060, and 2061-2080), *S. cernua* is expected to have the largest high-suitability area, as indicated in Table 3. Compared to the medium and the high-suitable areas, the low-suitable areas have a smaller proportion of the four species from Saxifragaceae. Figures 2-5 illustrate that these areas are concentrated in the northwestern part of the QTP. On the other hand, the middle-high suitable areas occupy a larger proportion, and the high-suitability areas cover over 6.0×10^5 km^2. Across the four species, the unsuitable areas have decreased in size from the past to the future, indicating an overall trend of contraction. In contrast, the highly suitable areas have shown a trend of expansion from the past to the future.

Migration trend of four species from Saxifragaceae with elevation gradient at different periods

The mean elevation of the potential distribution of Saxifragaceae in the specified area decreased with the increase in elevation, as demonstrated in Tables 3-4. This indicates that the distribution range of Saxifragaceae species generally decreased with increasing elevation. In the highly suitable areas, the average elevation of the potential distribution for Saxifragaceae was 3,332 m across different periods (Tables 3-4).

Table 3 Area of the species from Saxifragaceae under climatic scenarios in different periods 10k (km^2).

Species	Fitness grade	LGM	MH	1970-2000	2021-2040	2041-2060	2061-2080
Saxifraga cernua	unsuitable	60.86	58.99	70.09	38.98	33.90	32.10
	low suitable	48.72	46.94	76.20	68.48	56.42	65.02
	mid suitable	66.96	80.94	64.26	65.40	65.47	72.75
	high suitable	73.46	63.13	39.45	77.14	94.22	80.13
Saxifraga tangutica	unsuitable	99.87	90.55	110.26	91.72	116.51	100.36
	low suitable	53.52	48.19	44.10	46.55	47.53	44.26
	mid suitable	51.96	49.20	44.10	57.32	57.19	50.88
	high suitable	44.65	62.05	41.37	54.41	28.77	54.49
Saxifraga przewalskii	unsuitable	119.54	133.24	132.11	123.43	123.75	125.36
	low suitable	58.04	41.77	61.62	48.20	49.23	47.90
	mid suitable	43.36	48.48	36.46	51.93	48.66	52.67
	high suitable	29.06	26.52	19.81	26.44	28.37	24.07
Saxifraga unguiculata	unsuitable	94.22	95.26	106.89	109.80	101.06	98.59
	low suitable	65.78	58.60	68.98	68.12	69.36	72.50
	mid suitable	45.75	47.99	38.86	37.25	37.06	28.83
	high suitable	44.24	48.15	35.27	34.84	42.53	50.08

Table 4 The average elevation of land that could potentially support life for four different species under the present climate conditions.

Species	Low	Mid	High	Unit
Saxifraga cernua	4,100	3,900	3,800	m
Saxifraga tangutica	3,800	3,650	3,400	m
Saxifraga przewalskii	3,200	3,000	2,260	m
Saxifraga unguiculata	4,200	3,952	3,500	m

Among the four species of Saxifragaceae, *S. cernua* was observed grow at the highest average elevation, while *S. przewalskii* was found at the lowest average elevation. Generally, the five areas with unsuitable or low-suitability for these plants were concentrated at high elevation, whereas those with middle-high suitable region were located at lower elevation. The five areas with high suitability tended to shift towards lower elevation, primarily towards the southeast of the QTP, northern Yunnan, and western Sichuan. The regions with middle and highly suitable areas were becoming increasingly concentrated. According to Tables 3-4 and Figures 2-5, areas in middle and highly suitable region are expected to continue the migration southward under projected climate change.

Discussion

In our study on the influences of environmental factors on the potential distribution of Saxifragaceae species, we aimed to understand how elevation, slope, and climatic variables like temperature and precipitation impact species distribution. Our findings confirmed the significant role of elevation, offering a new understanding of species-environment interactions, especially in the context of climate change. These results not only align with previous studies emphasizing climatic factors as primary determinants of species range but also provide novel insights into the complex interplay of biological and environmental factors. The implications of our study are significant for conservation strategies, suggesting the need for targeted efforts in areas like the Qinghai-Tibet Plateau, where elevation and climate variables play a crucial role. Overall, our research contributes to the broader body of work on species distribution and offers valuable insights for future research and conservation efforts, particularly in the face of ongoing climate change.

Influences of environmental factors on the potential distribution of the species from Saxifragaceae

Despite some studies on the topic, there are still many gaps in understanding the species distribution of Saxifragaceae. To address this, we conducted in-depth research and found that elevation, slope, bio1, bio3, bio15, and bio16 are key environmental variables that impact the potential species distribution of Saxifragaceae, with elevation having the most significant effect. Environmental variables consist of both biological and abiotic components, with climatic factors primarily determining a species' range and dispersion pattern across a vast area. The species distribution also depends on broad-scale hydrothermal conditions, including temperature and precipitation. Biological and environmental factors directly affecting species distribution typically have a small-scale geographical impact and can have a complex effect on distribution. However, at larger geographical scales, the impact of these factors is likely to be less important due to reduced interactions between species[25]. Therefore, our study employed common large-scale bioclimatic factors to simulate the distribution range and pattern of four Saxifragaceae species[26].

The species distribution is affected by environmental conditions. Climate variables, such as temperature and precipitation, significantly impact a species' physiological and reproductive capabilities, affecting critical biological processes, such as dispersion ability, home range size, and survival under unfavorable conditions[27]. These climate-based characteristics can synchronize several critical biological processes of a species, including dispersion ability, home range size[28], and survival under unfavorable conditions[29]. However, the impact of climate variables is not universal, as other edaphic and topographic factors and interactions among biotic and abiotic environments can significantly affect the species distribution[30].

Overall, our findings highlight the importance of environmental variables, particularly elevation, in shaping the potential distribution of Saxifragaceae species. Furthermore, the emphasis on elevation in our study is insightful, considering that in mountainous regions such as the QTP, elevation can be a proxy for a multitude of ecological gradients, not just climate but also soil composition, vegetation types, and biological interactions. By integrating larger scale bioclimatic factors with the nuanced, location-specific variables like elevation, your research seems to offer a more comprehensive view of the Saxifragaceae distribution. This approach not only substantiates the effects of broad-scale hydrothermal conditions but also respects the complexity of species-environment interactions at a finer scale. Further studies will be needed to understand the complex interplay between different environmental factors and their impact on species distribution.

Species potential distribution of the family Saxifragaceae

In this study, the MaxEnt model was used to analyze how the distribution areas of four species of Saxifragaceae in different periods changed with time. The research results show that we use the AUC value to evaluate the predictive performance of our model running, a commonly used criterion by ecologists to assess the accuracy of niche modeling and species distribution modeling[31]. AUC is also extensively utilized to evaluate the accuracy of habitat suitability models[31]. AUC obtained in this study is greater than or equal to 90, which conforms to the modeling standard. Therefore, the predicted results are deemed more accurate and reliable. We conducted a comprehensive investigation to explore the distribution of four species from Saxifragaceae on the QTP under different climatic scenarios (past, present, and future). Our findings indicated that the species' distribution range was the largest on the southeastern QTP in the highly suitable region.

Climate change was an important factor affecting the potential distribution of Saxifragaceae species on the QTP. There were significant influences of the annual precipitation and mean temperature of the driest quarter on the potential distribution of Saxifragaceae species, which may be associated with the growing elevation of different orchid species because elevation shows complicated climate factors, such as humidity and temperature[32]. We guess the Saxifragaceae species distribution was found to be mainly climate driven because the total gain of the MaxEnt model was largely influenced by temperature and precipitation. The species distribution of Saxifragaceae has been observed to decrease with elevation across past, present, and future climate scenarios. One reason for this is that as elevation increases, there is a decrease in temperature and an increase in precipitation, leading to changes in the microclimate that can affect plant growth and survival[33]. The species from Saxifragaceae are adapted to specific environmental conditions, and changes in temperature and precipitation can disrupt their ability to survive and reproduce. Past climate scenarios have shown that during periods of global cooling, many plant species shifted their ranges to lower elevations[34,35,36]. Similarly, in present-day climate scenarios, it has been observed that species from Saxifragaceae are shifting their distributions to lower elevations, in response to rising temperatures and changes in precipitation patterns. Future climate scenarios predict that temperatures will continue to rise, and precipitation patterns will become more erratic. This could result in further range shifts of species from Saxifragaceae as they try to adapt to changing conditions. Additionally, if the rate of climate change is too rapid, some species may not be able to adapt quick enough and could face extinction.

Our investigation focused on a gradient stretch that began well above the mid-elevation. However, the widely observed decline in species diversity at greater elevations may also be due to the conical structure of mountains, which reduces available area[35]. Previous studies have shown that species richness is the highest in the middle elevation zone and decreases in both the high and low elevation zones[37]. Our findings demonstrated that various elevation had distributed peaks of Saxifragaceae species in the middle elevation region. Additionally, the higher distribution of *S. przewalskii* in the low-elevation area may be related to the higher temperature in that region.

Potential distribution and migration trends of the species from Saxifragaceae in different climate periods

The observed habitat suitability trends among *Saxifraga* species underscore the diverse adaptive strategies plants employ in response to environmental shifts. *Saxifraga cernua* demonstrates an evolutionarily impressive adaptability, potentially attributable to genetic factors, phenotypic plasticity, and potential symbiotic relationships[38]. In contrast, the consistent presence of *Saxifraga unguiculata* across varied habitats suggests its broader ecological amplitude, likely indicative of its ability to tolerate diverse environmental conditions[39]. However, *Saxifraga przewalskii*'s predominant residence in unsuitable habitats presents conservation concerns, warranting measures such as habitat restoration or assisted migration[40]. Monitoring and further research can provide a holistic understanding of their ecological dynamics in the face of ongoing environmental change[41].

In the current climate scenario, four species primarily inhabit the intersection zone between the southeastern QTP, western Sichuan, and northern Yunnan. High elevation, cold temperatures, and aridity are the main environmental factors influencing these suitable habitat areas of species[42]. Under climate change scenarios, from the last glacial age to the middle Holocene, the highly suitable habitats for these four species shifted eastward, from the northwest of the QTP to its southeast. These highly suitable areas were predominantly found in the southeastern QTP, western Sichuan, and northern Yunnan.

In future climate scenarios, these four species' high and medium-suitable habitat areas are expected to increase slightly compared to the current climate. This may be attributed to the availability of moisture and low temperatures in these regions, resulting in viable distributions for these species' climate change[43,44]. However, potentially suitable habitats' area and distribution patterns will likely remain stable. This stability could be due to the complex topographic structure created by the Qinling-Qilian Shan-Kunlun Mountain system along the eastern margin of the QTP, which prevents the long-distance dispersal of these four species. Additionally, the continuous distribution of valleys and mountains in lake basins provides secure local refuges, creating a unique and stable narrow distribution pattern. Consequently, it can be concluded that future climate change is unlikely to significantly threaten these species.

Conservation and management implications

Effectively allocating conservation resources require identifying areas of high conservation value[45]. Under extreme conditions, locales where species can seek refuge and persist, are termed biological sanctuaries, which safeguard the survival of organisms and biodiversity under unfavorable climatic conditions, often characterized by a notable contraction in the distribution range[46]. Through the comparative analysis of Saxifragaceae's past, present, and future habitats, we deduced that the southeastern region of the QTP constitutes the most favorable habitat for these species. This conclusion is based on several factors: first, the relatively low elevation of approximately 3,000 meters; second, the temperate climate facilitated by the Brahmaputra Valley, which permits the ingress of summer monsoons; and third, the copious precipitation prevalent in this region. As a result, we identify the southeastern QTP as a sanctuary and appropriate distribution zone for Saxifragaceae species under prospective climate change scenarios.

Considering these findings, we propose the creation of a nature reserve for Saxifragaceae species on the southeastern QTP. According to the results, the overall suitable distribution area of the four species is very low in the entire QTP, and the high suitable area is only concentrated in the southeast of the QTP. The potential distribution area of the highly suitable species of Saxifragaceae is 1,431 km^2 (1.7% of the QTP) and there is a trend of southward migration. In more than 80 percent of the QTP, the Saxifragaceae species have few distributions, Therefore, it is necessary to establish a protected area in the southeastern region of QTP. This reserve would serve as a response model to climate change, promoting the dynamic conservation of these taxa in the future and mitigating the risks of endangerment and extinction due to climate change.

Conclusion

Climate change has an important impact on the distribution of endangered Saxifragaceae species in the QTP. Our study highlights the importance of integrating climate change projections into species distribution models to enhance our understanding of potential impacts on these species and inform conservation efforts. Moreover, it emphasizes the need for adaptive management strategies that take into account the dynamic nature of species distributions as they respond to evolving climatic conditions.

By analyzing data from historical, current, and future climate scenarios, our study pinpointed several environmental variables that significantly influence the potential distribution of endangered Saxifragaceae in the QTP. These variables encompass elevation, slope, mean annual temperature, isothermality, precipitation seasonality, and precipitation during the wettest quarter. The analysis also disclosed that the mean elevation of the potential distribution for Saxifragaceae species ranged from 2,260 m to 4,150 m across various climate scenarios.

Our findings propose that the southeastern QTP constitutes the largest highly suitable region for Saxifragaceae species under both current and future climate scenarios, and that species distribution is likely to decline with increasing elevation. To protect endangered Saxifragaceae species, we advocate prioritizing the establishment of protected areas in the southeastern QTP, western Sichuan, and northern Yunnan for future conservation planning. This strategy will contribute to the preservation of these species in the face of climate change and other environmental challenges.

Declarations

Data availability statement

The original contributions presented in this study are included in the article/supplementary material. We uploaded supporting data in an open data repository, Dryad (DOI: 10.5061/dryad.v9s4mw729). In our research, the collection of plant material was not required.

Author contributions

CS, TL and WC: Analyzing and interpreting the data and writing the original draft. XS and YL: Conceiving and designing the project. YZ, DW, XL, XM, CW, SW, NS and CS: Interpreting the data. MM: Polishing the paper. All authors have read and agreed to the published version of the manuscript.

Funding

This research was funded by the Qinghai Provincial Science and Technology Major Project (2023-SF-A5), the Second Tibetan Plateau Scientific Expedition and Research (STEP) Program (2019QZKK0502), the Wildlife Conservation Project from Central Forestry and Grassland Ecological Protection and Restoration Fund (QHSY-2023-016), the Forest and Grass New Technology Promotion Project from Qinghai Provincial Finance Forestry Reform and Development Fund (QSCZ-2023-001), the First Central Guidance on Local Science and Technology Development Fund of Qinghai Province (2023ZY019), and the National Natural Science Foundation of China (32360305, 32160297).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

1. Bellard, C. *et al*. Impacts of climate change on the future of biodiversity. *Ecol. Lett.* **15**(4), 365-377. https://doi.org/10.1111/j.1461-0248.2011.01736.x (2012).
2. Pecl, G. T. *et al*. Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Sci*. **355**(6332), eaai9214. http://dx.doi.org/10.1126/science.aai9214 (2017).
3. Hooper, D. U. *et al*. A global synthesis reveals biodiversity loss as a major driver of ecosystem change. *Nature*. **486**(7401), 105-108. https://doi.org/10.1038/nature11118 (2012).
4. Folk, R. A. *et al*. Biogeography and habitat evolution of Saxifragaceae, with a revision of generic limits and a new tribal system. Taxon 70(2): 263-285. https://doi.org/10.1002/tax.12450 (2021).
5. Gao, Q. B., Li, Y. H., Gornall, R. J., Zhang, Z. X., Zhang, F. Q., Xing, R., Fu, C. P., Wang, J. L., Liu, H. R., Tian, Z. Z., Chen, S. L. Phylogeny and speciation in *Saxifraga* sect. Ciliatae (Saxifragaceae): Evidence from *psb*A-*trn*H, *trn*L-F and ITS sequences. *Taxon*. **64**(4), 703-713. https://doi.org/10.12705/644.3 (2015).
6. GengJi, Z. M., Li, Y., Jia, L. K., Xia, M. Z. & Gao, Q. B. Phylogeography of *Saxifraga tagutica* Engi. (Saxifragaceae). *Acta Bot. Bor-Occid. Sin*. **38**(2), 370-380. https://doi.org/10.7606/j.issn.1000-4025.2018.02.0370 (2018).
7. Myers, N. *et al*. Biodiversity hotspots for conservation priorities. *Nature*. **403**(6772), 853-858. https://doi.org/10.1038/35002501 (2000).

8. Parmesan, C. Ecological and evolutionary responses to recent climate change. *Annu. Rev. Ecol, Evol, S.* **37**, 637-669. https://doi.org 10.1146/annurev.ecolsys.37.091305.110100 (2006).
9. Alexander, J.M. *et al.* Plant invasions into mountains and alpine ecosystems: current status and future challenges. *Alpine. Bot.* **126**, 89-103. https//doi.org/10.1007/s00035-016-0172-8 (2016).
10. Pyšek, P. *et al.* Scientists' warning on invasive alien species. *Biol. Rev.* **95**(6), 1511-1534. https://doi.org/10.1111/brv.12627 (2020).
11. Wang, S., Che, Y. & Ma, X. G. Integrated risk assessment of glacier lake outburst flood (GLOF) disaster over the Qinghai-Tibetan Plateau (QTP). *Landslides.* **17**, 2849-2863. https://doi.org/10.1007/s10346-020-01443-1 (2020).
12. Yang, W., Yao, L., Xie, H., Zhu, Z., Ni, H. & Ma, W. An assessment of using remote sensing-based models to estimate ground surface soil heat flux on the Tibetan plateau during the freeze-thaw process. *Remote. Sens-basel.* **12**(3), 1-28. https://doi.org/10.3390/rs12030501 (2020).
13. Feng, W., Lu, H., Yao, T. & Yu Q. Drought characteristics and its elevation dependence in the Qinghai-Tibet plateau during the last half-century. *Sci. Rep.* **10**(1), 14323. https://doi.org/10.1038/s41598-020-71295-1 (2020).
14. Xu, H., Wang, X. P. & Zhang, X. X. Alpine grasslands response to climatic factors and anthropogenic activities on the Tibetan Plateau from 2000 to 2012. *Ecol. Eng.* **92**, 251-259. https://doi.org/10.1016/j.ecoleng.2016.04.005 (2016).
15. Zurell, D., Franklin, J., König, C., Bouchet, P. J. & Merow, C. A standard protocol for reporting species distribution models. *Ecography.* **43**(9), 261-1277. https://doi.org/10.18452/22268 (2020).
16. Fick, S. E. & Hijmans, R. J. WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas. *Int. J. Climatol.* **37**, 4302-4315. https://doi.org/10.1002/joc.5086 (2017).
17. Yan, H. Y., Feng, L., Zhao, Y. F., Feng, L., Zhu, C. P., Qu, Y. F. & Wang, H. Q. Predicting the potential distribution of an invasive species, *Erigeron canadensis* L., in China with a maximum entropy model. *Global. Ecol. Conserv.* **21**, e00822. https://doi.org/10.1016/j.gecco.2019.e00822 (2020).
18. Shi, N., Naudiyal, N., Wang, J., Gaire, N. P., Wu, Y., Wei, Y., He, J. L. & Wang, C. Y. Assessing the impact of climate change on potential distribution of *Meconopsis punicea* and its influence on ecosystem services supply in the southeastern margin of the Qinghai-Tibet Plateau. *Front. Plant. Sci.* **12**, 830119. https://doi.org/10.3389/fpls.2021.830119 (2021).
19. Elith, J. *et al.* Novel methods improve prediction of species' distributions from occurrence data. *Ecography.* **29**, 129-151. https://doi.org/ 10.1111/j.2006.0906-7590.04596.x (2006).
20. Pearson, R. G., Raxworthy, C. J., Nakamura, M. & Peterson, A. T. Predicting species distributions from small numbers of occurrence records: a test case using cryptic geckos in Madagascar. *J. Biogeogr.* **34**, 102-117. https://doi.org/10.1111/j.1365-2699.2006.01594.x (2007).
21. Jose, S. & Nameer, P. O. The expanding distribution of the Indian Peafowl (Pavocristatus) as an indicator of changing climate in Kerala, southern India: a modelling study using MaxEnt. Ecol. Indic. **110**, 105930. https://doi.org/10.1016/j.ecolind.2019.105930 (2020).

22. Fourcade, Y., Engler, J. O., Rodder, D. & Secondi, J. Mapping species distributions with MAXENT using a geographically biased sample of presence data: A performance assessment of methods for correcting sampling bias. *PLoS*. *One*. **9**(5), e97122. https://doi.org/10.1371/journal.pone.0097122 (2014).
23. Peterson, A. T. & Cohoon, K. P. Sensitivity of distributional prediction algorithms to geographic data completeness. *Ecol*. *Model*. 117, 159-164. https://doi.org/10.1016/s0304-3800(99)00023-x (1999).
24. Brown, J. L. SDMtoolbox: A python-based GIS toolkit for landscape genetic, biogeographic and species distribution model analyses. *Methods*. *Ecol*. *Evol*. **5**, 694-700. https://doi.org/10.1111/2041-210x.12200 (2014).
25. Thuiller, W., Lavorel, S., Araújo, M. B., Sykes, M. T. & Prentice, I. C. Climate change threats to plant diversity in Europe. *Pnas*. **102**, 8245-8250. https://doi.org /10.1073/pnas.0409902102 (2005).
26. Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P. G. & Jarvis, A. Very high resolution interpolated climate surfaces for global land areas. *Int*. *J*. *Climatol*. **25**, 1965-1978. https://doi.org/10.1002/joc.1276 (2005).
27. Sharma, G. P. & Raghubanshi, A. S. Tree population structure, regeneration and expected future composition at different levels of *Lantana camara L*. invasion in the Vindhyan tropical dry deciduous forest of India. *Lyonia*. **11**(1), 25-37(2006).
28. Bradley, B. A. & Mustard, J. F. Characterizing the landscape dynamics of an invasive plant and risk of invasion using remote sensing. *Ecol*. *Appl*. **16**, 1132-1147. https://doi.org/10.1890/10510761(2006)016[1132:CTLDOA]2.0.CO;2 (2006).
29. Morris, W. F., Ehrlén, J., Dahlgren, J. P., Loomis A. K. & Louthan, A. M. Biotic and anthropogenic forces rival climatic/abiotic factors in determining global plant population growth and fitness. *Pnas*. **117**(2), 1107-1112. https://doi.org/10.1073/pnas.1918363117 (2019).
30. Norberg, A. *et al*. A Comprehensive evaluation of predictive performance of 33 species distribution models at species and community levels. *Ecol*. *Monogr*. **89**, e01370. https://doi.org/10.1002/ecm.1370 (2019).
31. Allouche, O., Tsoar, A., & Kadmon, R. Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). *J*. *Appl*. *Ecol* **43**, 1223-1232. https//doi.org/10.1111/j.1365-2664.2006.01214.x (2006).
32. Tsiftsis, S., Tsiripidis, I., Karagiannakidou, V. & Alifragis, D. Niche analysis and conservation of the orchids of east Macedonia (NE Greece). *Acta*. *Oecol*. *Int*. *J*. *Ecol*. **33**, 27-35. https://doi.org/10.1016/j.actao.2007.08.001 (2008).
33. Moradi, H. & Oldeland, J. Climatic stress drives plant functional diversity in the Alborz Mountains, *Iran.* Ecol. Res. **34**, 171-181. https://doi.org/10.1111/1440-1703.1015 (2019).
34. Lomolino, M. V., Riddle, B. R. & Whittaker R. J. Biogeography (4th ed.). Sunderland: Sinauer Associates. (2010).
35. McCain, C. M. Global analysis of reptile elevational diversity. *Global*. *Ecol*. *Biogeogr*. **19**, 541-553. https://doi.org/10.1111/j.1466-8238.2010.00528.x (2010).

36. Sanders, N. J. & Rahbek, C. The patterns and causes of elevational diversity gradients. *Ecography*. **35**, 1-3. https://doi.org/10.1111/j.1600-0587.2011.07338.x (2012).
37. McCain, C. M. The mid-domain effect applied to elevational gradients: Species richness of small mammals in Costa Rica. *J. Biogeogr*. 31, 19-31. https://doi.org/10.1046/j.0305-0270.2003.00992.x (2004).
38. Birks, H. J. B. & Willis, K. J. Alpines, trees, and refugia in Europe. *Plant*. *Ecol*. *Divers*. **1**(2), 147-160. https://doi.org/10.1080/17550870802349146 (2008).
39. Holt, R. D. Bringing the Hutchinson a niche into the 21st century: ecological and evolutionary perspectives. *Pnas*. **106**(supplement_2), 19659-19665. https://doi.org/10.1073/pnas.0905137106 (2009).
40. Pellissier, L. *et al*. Thermal niches are more conserved at cold than warm limits in arctic-alpine plant species. *Global*. *Ecol*. *Biogeogr*. **22**(8), 933-941. https://doi.org 10.1111/geb.12057 (2013).
41. Vogt, M. *et al*. Habitat suitability and ecological niches of different plankton functional types in the global ocean. In EGU General Assembly Conference Abstracts (pp. EGU2013-9812).(2013).
42. Cheng, G. D. & Wu, T. H. Responses of permafrost to climate change and their environmental significance, Qinghai-Tibet Plateau. *J*. *G*. *R*: *Earth*. *Surface*. **112**, F02S03. https://doi.org/10.1029/2006JF000631 (2007).
43. Chen, I. C. *et al*. Rapid range shifts of species associated with high levels of climate warming. *Sci*. **333**, 1024-1026. https://doi.org/10.1126/science.1206432 (2011).
44. Fei, S. L. *et al*. Divergence of species responses to climate change. *Sci*. *Adv*. **3**, e1603055. https://doi.org/10.1126/sciadv.1603055 (2017).
45. Li, J. *et al*. Beissinger S R. Defining priorities for global snow leopard conservation landscapes. *Biol*. *Conserv*. **241**, 108387. https://doi.org/10.1016/j.biocon.2019.108387 (2020).
46. Tzedakis, P. C., Lawson, I. T., Frogley, M. R., Hewitt, G. M. & Preece, R. C. Buffered tree population changes in a Quaternary refugium: evolutionary implications. *Sci*. **297**(5589), 2044-2047. https://doi.org/10.1126/science.1073083 (2002).

Figures

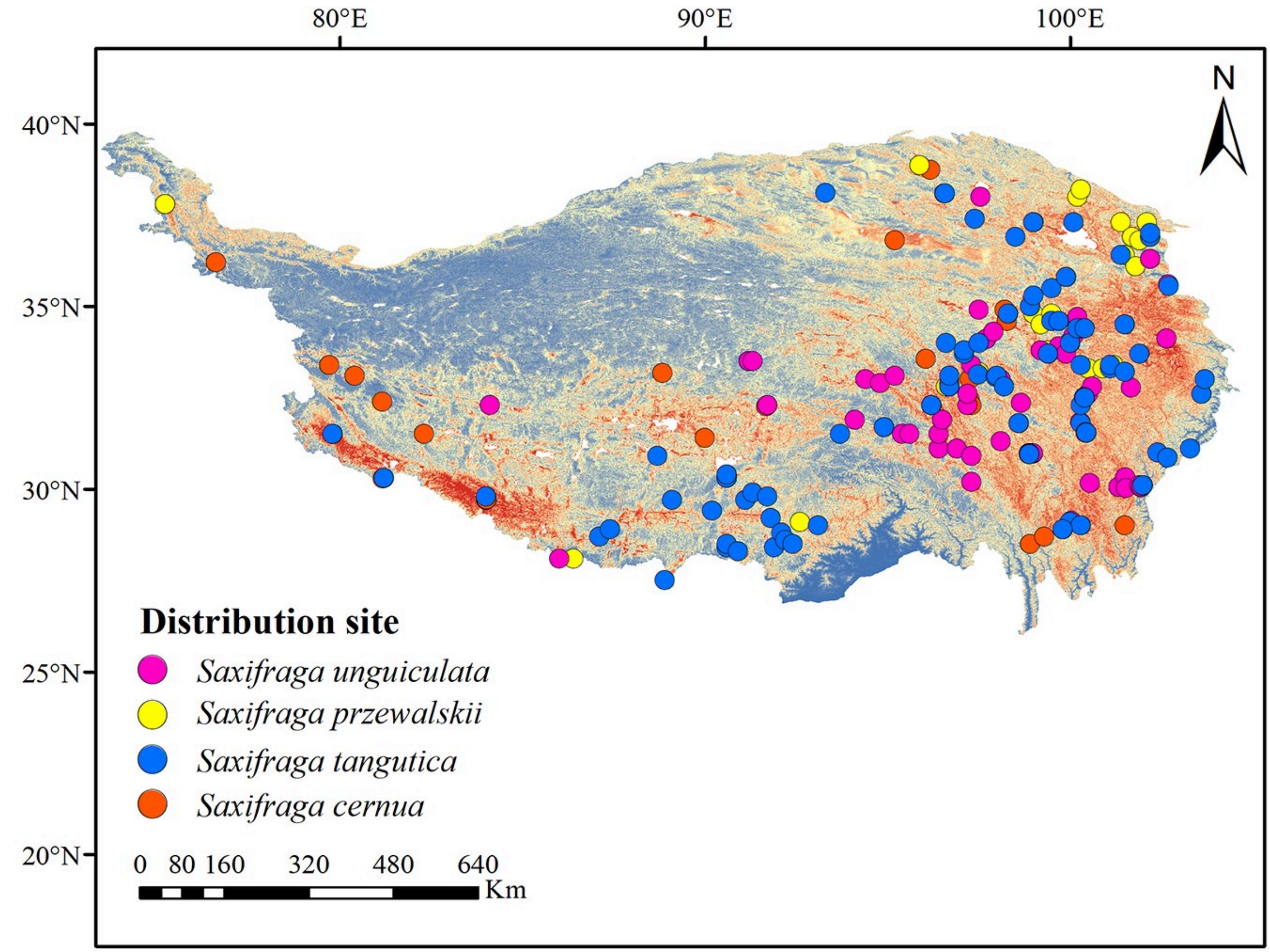

Figure 1

Location point map of four Saxifragaceae species.

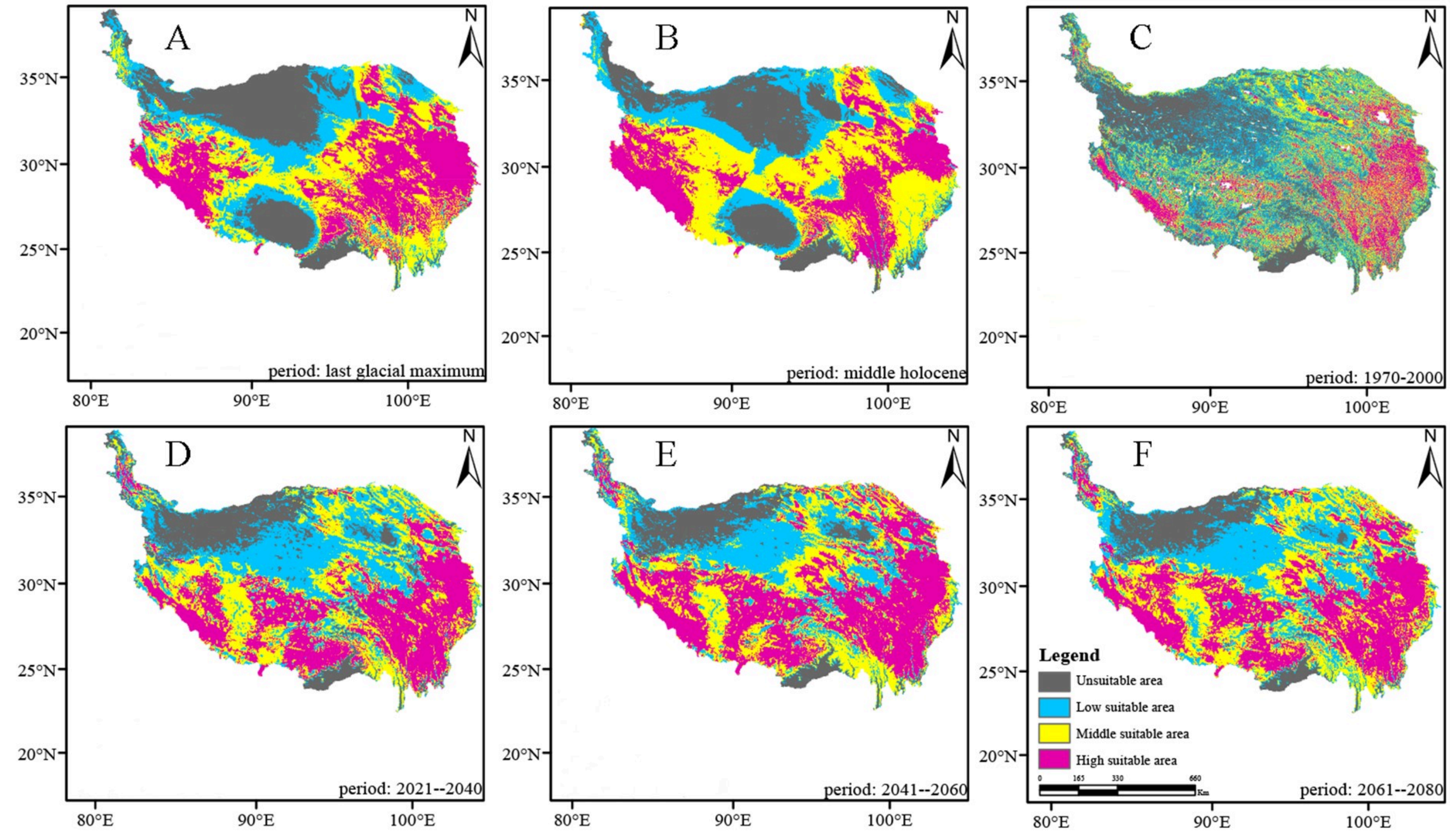

Figure 2

The change of distribution pattern of *Saxifraga cernua*. A: stand for last glacial maximum; B: stand for middle Holocene; C: stand for 1970-2000; D: stand for 2021-2040; E: stand for 2041-2060; F: stand for 2061-2080.

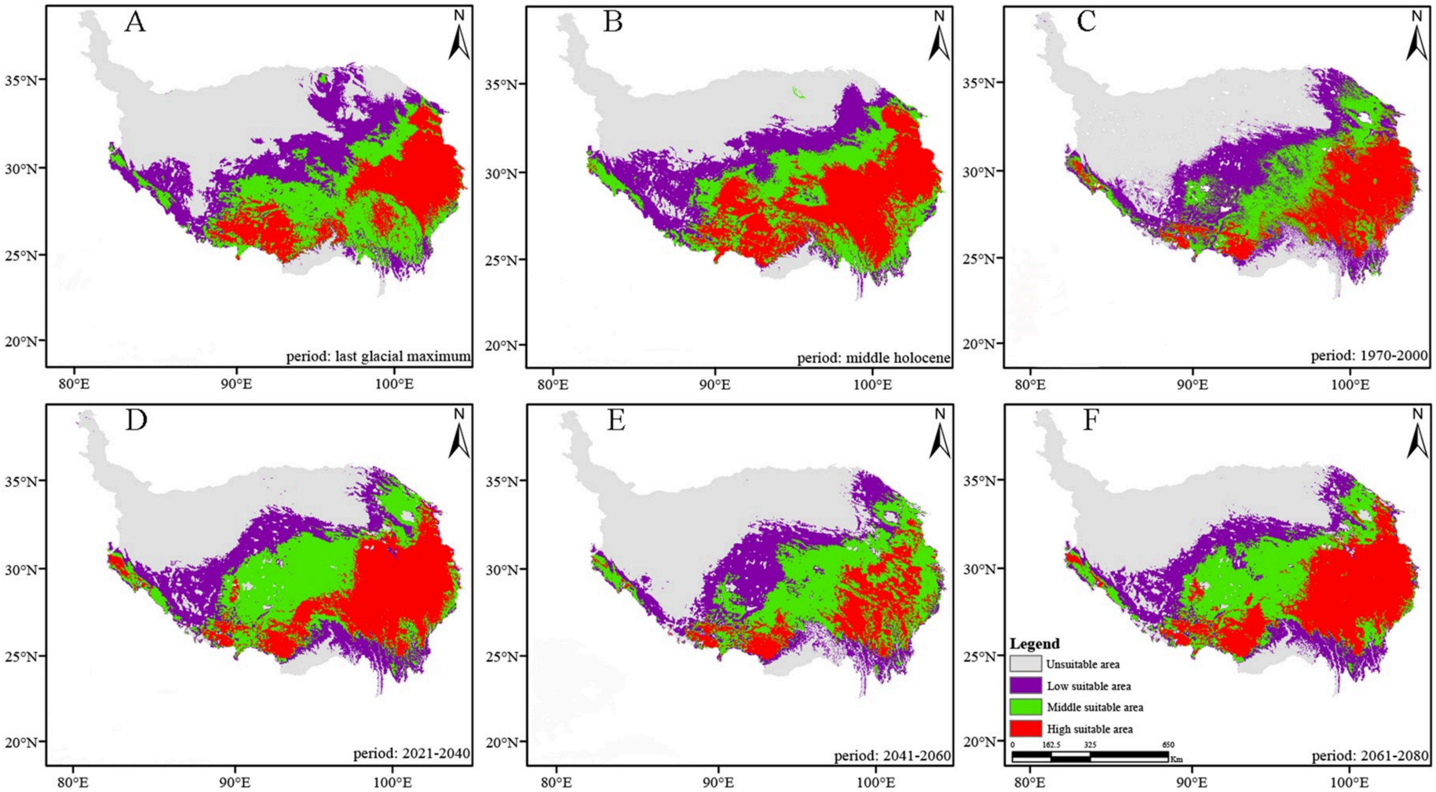

Figure 3

The change of distribution pattern of *Saxifraga tangutica*. A: stand for last glacial maximum; B: stand for middle Holocene; C: stand for 1970-2000; D: stand for 2021-2040; E: stand for 2041-2060; F: stand for 2061-2080.

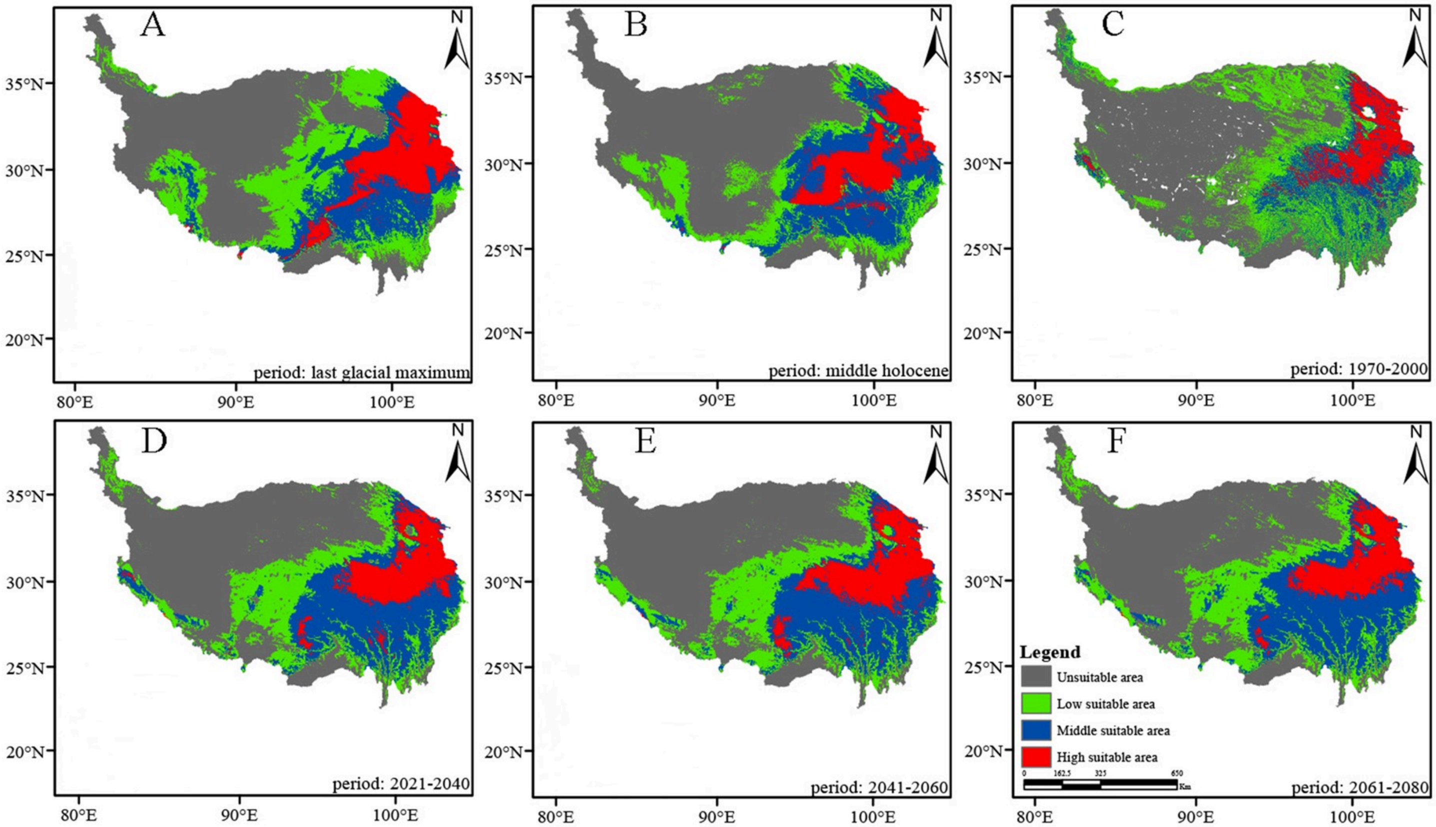

Figure 4

The change of distribution pattern of *Saxifraga przewalskii*. A: stand for last glacial maximum; B: stand for middle Holocene; C: stand for 1970-2000; D: stand for 2021-2040; E: stand for 2041-2060; F: stand for 2061-2080.

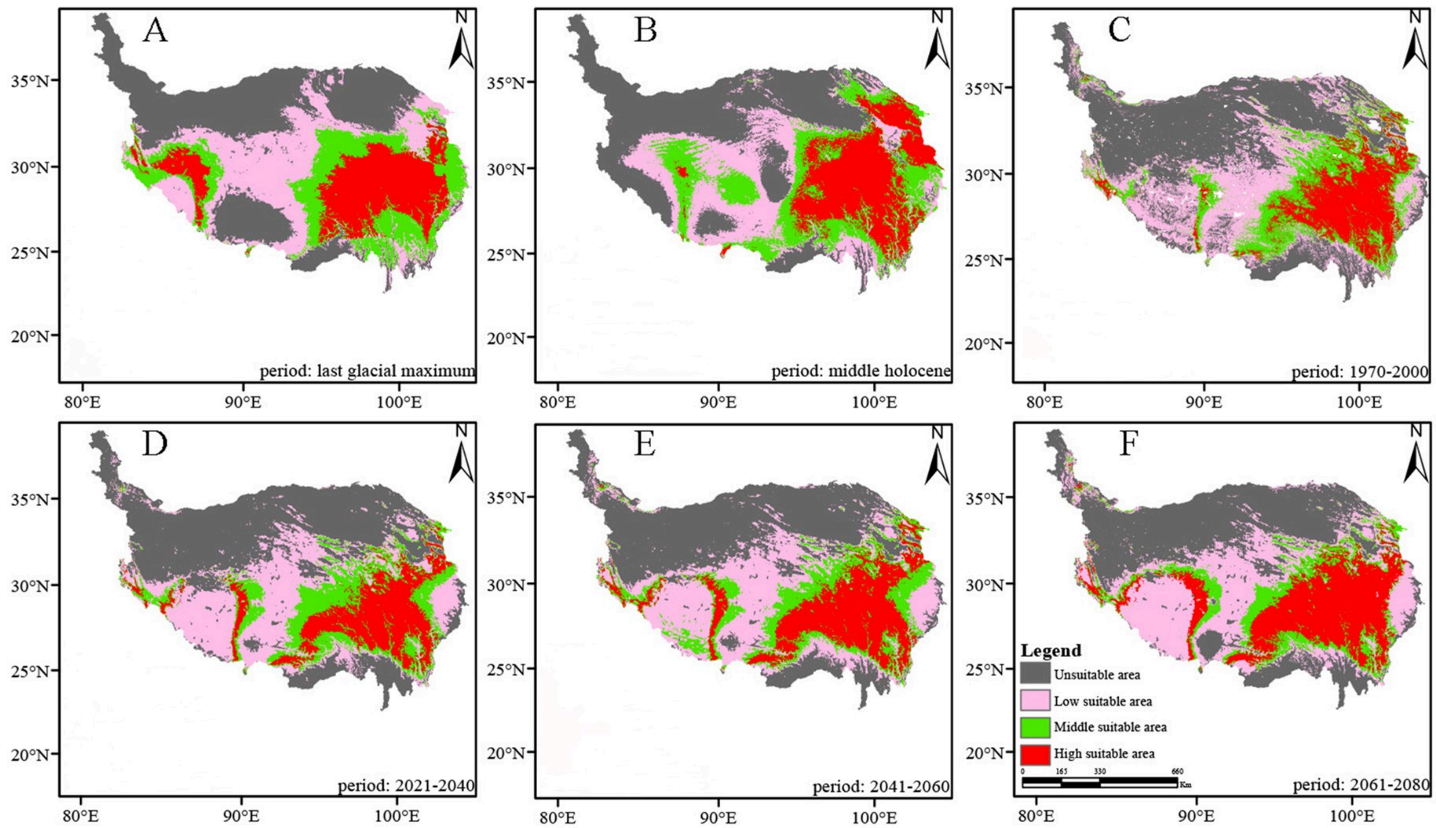

Figure 5

The change of distribution pattern of *Saxifraga unguiculata*. A: stand for last glacial maximum; B: stand for middle Holocene; C: stand for 1970-2000; D: stand for 2021-2040; E: stand for 2041-2060; F: stand for 2061-2080.

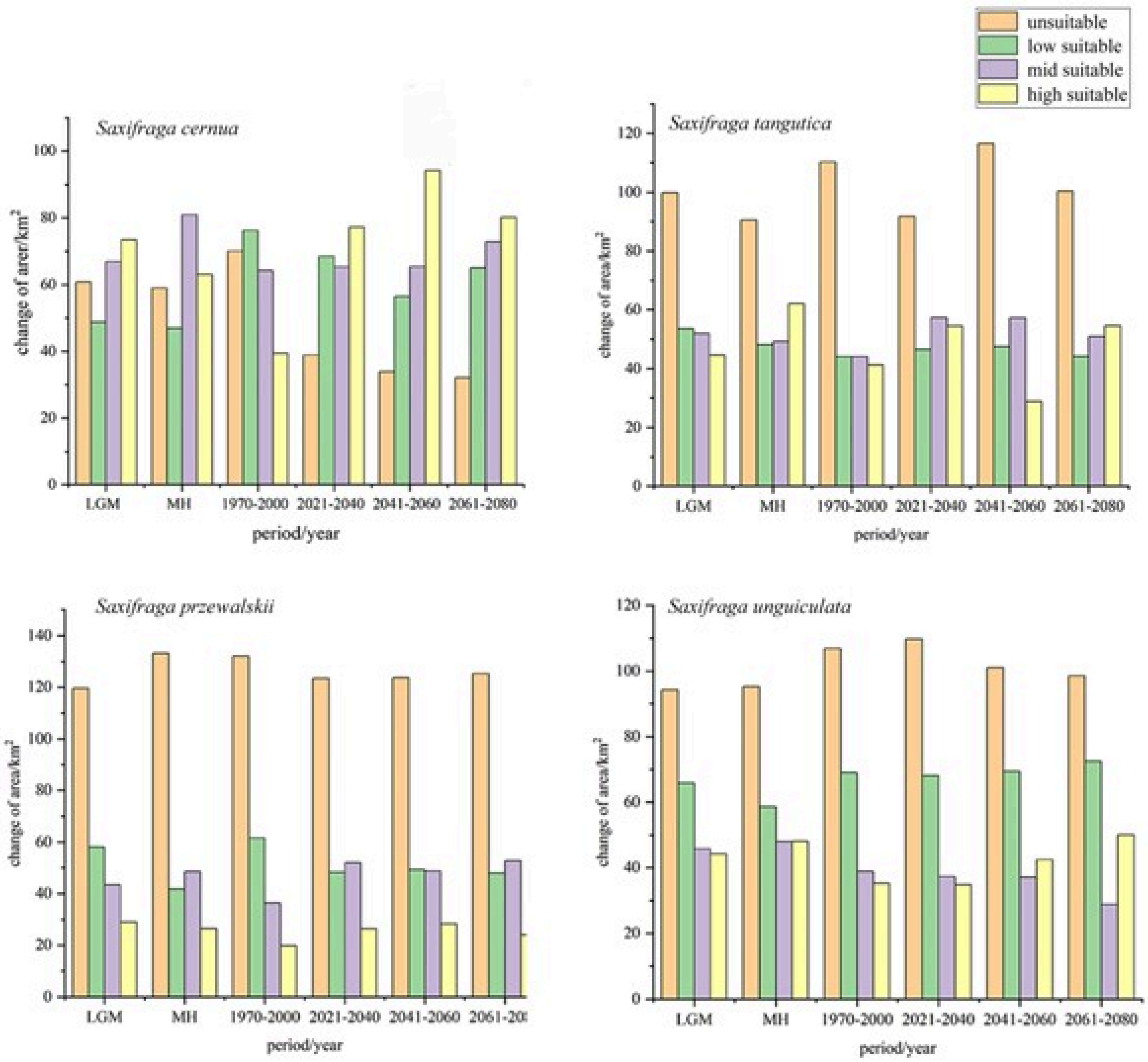

Figure 6

Changes of suitable area of Saxifragaceae species.