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Distribution and Conservation of Plants in the Northeastern Qinghai–Tibet Plateau under Climate Change

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Abstract: Climate change is causing unprecedented alterations in the spatial pattern of global biodiversity, imposing severe challenges for biodiversity conservation. In particular, alpine biomes are sensitive to a variety of environmental changes. Therefore, understanding the distribution and conservation of alpine plant biodiversity is vital. In this study, we used species distribution modeling and 20,650 high-resolution occurrence coordinates of 1224 plant species to evaluate the potential distribution of plants in the northeastern Qinghai–Tibet Plateau (Qinghai Province, China) under different future climate scenarios, through an integrative analysis of species distribution probabilities, species richness, and priority conservation areas. Under current and future climate scenarios, the plant species are predicted to be mainly distributed in eastern and southern Qinghai Province, with the suitable conditions for plant species gradually extending from the southeast to the northwest of Qinghai Province under the effects of climate change. The priority conservation areas in Qinghai national nature reserves are predicted to expand, with this expansion being greater for herbaceous plants than woody plants, under future climate scenarios. However, the priority conservation areas outside nature reserves in Qinghai Province remain approximately three times larger than those inside nature reserves. Thus, there were great differences between the existing nature reserve area and the priority conservation areas, with nature reserves insufficiently covering priority conservation areas in Qinghai Province. Therefore, the original nature reserve areas should be expanded, according to the predicted plant habitat hotspots in Qinghai Province. Our research provides valuable information for biodiversity protection in the northeastern Qinghai–Tibet Plateau, reasonable strategies for addressing the future protection challenges associated with climate pressure, and new insights for improving nature reserves in the Qinghai–Tibet Plateau.

Keywords: alpine biodiversity hotspot; climate change; species distribution model; natural reserve; Qinghai province; Zonation

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1. Introduction

Global climate change has seriously affected the physiological state, geographical distribution, and growth cycle of plants, pushing many species to the verge of extinction [1–3]. Climate change poses a major threat to biodiversity [3–5]. Furthermore, with increasing temperatures and precipitation, this threat is growing [6]. As global warming and changing precipitation patterns will affect the physiological and ecological processes of many plant populations, it is expected to become a more serious threat to ecosystems over the next few decades [1,2,7]. Previous studies have shown that climate change has caused great changes in terms of the growth, degradation, and migration of plant species populations [1,3,8–10]. These effects may intensify in the future [1,3,8–10].

Nature reserves play an important role in the protection of plant biodiversity under global climate change [5,11]. Natural selection provides a mechanism for species to adapt to environmental changes [12,13]. However, recent studies have shown that future climate changes may cause substantial contractions of species distributions, as well as local extirpations within existing nature reserves, thus reducing the effectiveness of nature reserves in protecting target species [14]. For example, Araujo et al. found that, by the 2080s, the distributions of plant and vertebrate species in Europe are expected to exhibit significant reduction, shrinkage, or disappearance [15]. The authors also found that, in 2000, some species were no longer protected by reserves, thus reducing their effectiveness in protecting plant species [15]. Under the influence of future climate change, the area of suitable habitats for some plant species are likely to decrease. This suggests that some nature reserves may not cover the distribution of plant species under future climate scenarios, resulting in conservation gaps [16,17]. Exploring the effectiveness of existing nature reserves is essential for comprehensive biodiversity conservation planning [17,18].

Some studies have shown that protecting the habitats of species is one of the measures that can be taken to promote species restoration [19]. Predicting the potential habitat distributions of species and then selecting appropriate priority conservation areas (PCAs) is an important issue that requires data on the potential habitat for these plant species [20]. Modeling the distribution of potential habitats of plant species provides a means to determine such habitats [19,20]. More and more reserve planners and managers have designed projects to promote systematic conservation planning [21,22]. PCAs are locations designated for the protection of natural habitats and the preservation of open space for future generations. They are used to design minimum reserves for plant species, minimizing the effective space required for conservation areas to meet protection requirements [21,22].

Alpine mountain biomes are a hotspot of plant biodiversity and are very sensitive to a variety of environmental changes [23,24]. Due to its high habitat heterogeneity, the Qinghai–Tibet Plateau has rich and diverse plant life, and is also an important refuge for a variety of endemic and wide-distributed alpine species [21]. Due to its high species diversity, it is considered to be one of the most important biodiversity hotspots in the world [25–29]. The research area in this study is the Qinghai Province of China, which is located in the northeast of the Qinghai–Tibet Plateau and comprises an important alpine research area [17]. It is a traditionally sparsely populated area with various climatic zones and natural habitats [20]. It is also one of the most sensitive areas to global warming in the world, providing an important habitat for a unique combination of species. Increased temperature and precipitation in some areas may lead to severe challenges for the protection of biodiversity in Qinghai Province [17,20]; however, it remains unclear how climate change will affect the plant diversity in Qinghai Province.

In the present study, we focus on the probability of successfully protecting plant species in Qinghai Province, China. We divide the plants in Qinghai Province into woody and herbaceous species, and discuss these two types respectively in order to formulate more appropriate strategies to protect the diversity and distribution area of plant species in Qinghai Province. In future climate scenarios, the temperature will increase [30]. Furthermore, it is well-known that plants are highly sensitive to climate change [5,31]; for example, some studies have shown that drought will exacerbate the general death of trees and shrubs, which clearly merits consideration [32–34]. As the basic components of ecosystems, the loss of herbaceous and woody plants will have serious consequences on ecosystem functions [9,35]. Therefore, the conservation of plant diversity under climate change must urgently be considered.

The impact of climate change on species suitability distributions is usually evaluated using species distribution models [36]. These niche-based models predict the probabilities of species distributions and the areas that are suitable for the establishment of various species by analyzing the relationship between species distributions and environmental variables [7]. On this basis, we used 20,650 georeferenced data throughout Qinghai Province to evaluate the current and future geographical patterns of plant species in Qinghai Province, as well as to evaluate the effectiveness of existing protected areas for plant protection in Qinghai Province. This study was carried out to achieve the following aims: (a) determine the impact of specific environmental and climatic factors on plant species suitability and distributions in Qinghai Province; (b) predict the potential impact of climate change on the distributions of woody and herbaceous species in Qinghai Province; and (c) to assess the conservation effectiveness of existing nature reserves on plant species under predicted climate change scenarios.

2. Materials and Methods

2.1. Study Area

Qinghai Province is one of the hotspots of alpine biological community plant biodiversity and is very sensitive to various environmental changes [23,24]. Qinghai Province is the northeast portion of the Qinghai–Tibet Plateau, with an average altitude of more than 3000 m. It is a mountainous area characterized by high altitude, perennial low temperatures, and a layer of permafrost beneath the soil. Qinghai Province is the source of the Yellow River, the Yangtze River, and the upper reaches of the Lancang River [28,37]. It is characterized by the continental climate of the plateau. The annual average temperature is between −5.6 and 8.6 °C, and the annual precipitation is 15–750 mm [37]. From the past to the present, the temperature has exhibited an obvious upward trend, and precipitation has also increased substantially [38,39]. In addition, it features unique ecosystem and habitat diversity [17]. Qinghai Province is an important part of the alpine forest ecosystem of the Qinghai–Tibet Plateau. It is also an important ecological security barrier for the area known as the "Chinese water tower" [28] and plays an important role in maintaining plant diversity. Therefore, Qinghai Province is widely recognized as a hotspot of alpine biodiversity. Sanjiangyuan Nature Reserve, the largest nature reserve in China, is located in the hinterland of the Qinghai–Tibet Plateau, which contains both unique and typical alpine ecosystems [29]. It is not only a typical representative of the alpine environment of the Central Asian plateau and the world's alpine grasslands but is also a biodiversity hotspot [35]. Therefore, the study of plants in Qinghai Province is of particular importance.

There are seven national nature reserves in Qinghai Province [40]. Data on the national nature reserves were downloaded from the Resource and Environmental Science and Data Center (https://www.resdc.cn/Default.aspx (accessed on 13 February 2021)), by searching the National Nature Reserve boundary data on the website and downloading the geographic information data for China's nature reserves. From smallest to largest, they include Longbao National Nature Reserve (LB), Xunhua Mengda National Nature Reserve (XHMD), Datong Beichuan Heyuan District National Nature Reserve (DTBCHYD), Qinghai Chaidamu Haloxylon ammodendron Forest National Nature Reserve (QHCDMHA), Qinghai Lake National Nature Reserve (QHL), Kekexili National Nature Reserve (KKXL), and Sanjiangyuan National Nature Reserve (SJY); see Figure 1.

2.2. Species Distribution Data

The georeferenced data of plants in the Qinghai Province of China were obtained from the flora of China, the flora of Qinghai Province, the National Plant Specimen Resource Center (NPSR; https://www.cvh.ac.cn/ (accessed on 21 February 2021)), and the Global Biodiversity Information Facility (GBIF; https://www.gbif.org/ (accessed on 23 February 2021)) network databases. All extracted occurrence data were rasterized as presences at a resolution of 10.0 arc-minute cells (16.0 km at the equator), in order to reduce the effect of sampling bias and to avoid errors associated with georeferencing, obvious misidentifications, and duplicate records per grid cell. Each occurrence record was checked based on the habitat description using Google Maps [3,41]. Previous studies have shown that the performance of species distribution models depends on the sample size of the species distribution data [41]. Therefore, we excluded species with <5 presence points from the databases, and finally obtained species presence data for 1224 plant species, representing indicator species of biodiversity conservation in Qinghai Province. Among these species, there were 5 species with more than 100 presence points and 53 species with over 50 presence points. The maximum number of occurrences was 146, while the minimum number of occurrences was 5. In addition, we divided the data for Qinghai Province into woody and herbaceous plants, including 162 and 1062 woody and herbaceous plant species, respectively (Table S1). As the physiological characteristics and habitats of woody and herbaceous plants differ [42], we observed the distribution probabilities of woody and herbaceous species separately in Qinghai Province, in response to climate change.

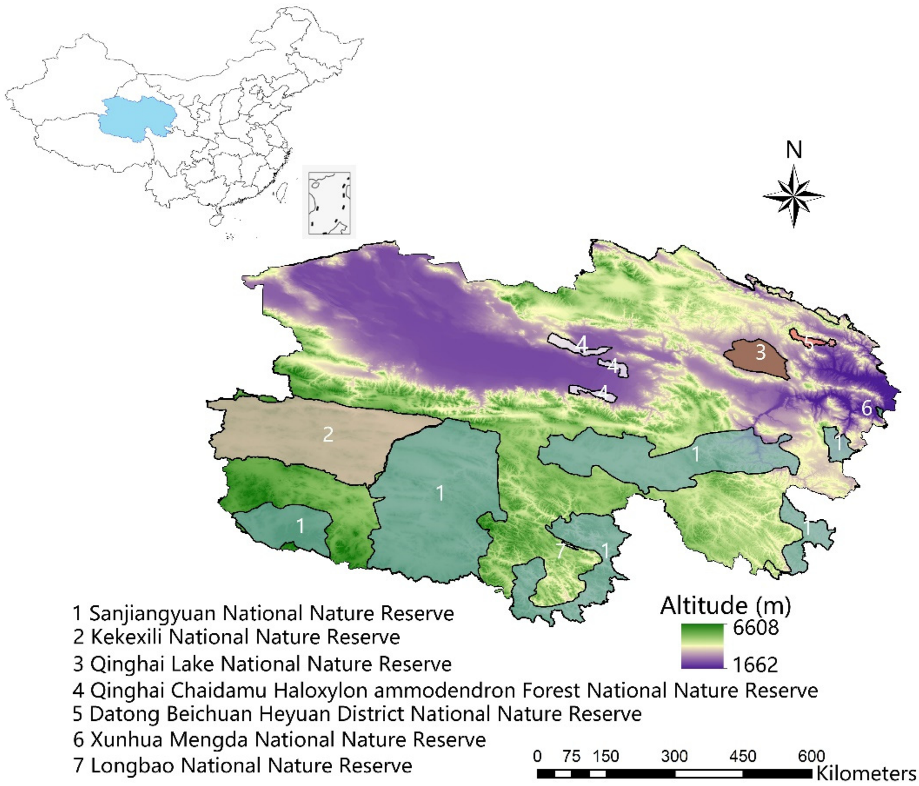

Figure 1. Distribution of the seven nature reserves in Qinghai Province.

2.3. Climatic and Topographic Data

We obtained a set of 19 bioclimate variables with 5 min spatial resolution from WorldClim (https://www.worldclim.org (accessed on 23 February 2022)), including both current climate (1950–2000) and future climate (2081–2100) scenarios [43]. We used a new set of emission scenarios, driven by different socio-economic assumptions [44]. The emissions scenarios include shared socio-economic pathways [44]. A number of these shared socio-economic pathway scenarios were selected to drive climate models for CMIP6 [44]. The data utilized here correspond to the latest IPCC-CMIP6 models [44]. Shared socio-economic pathway scenarios were based on narratives describing alternative socio-economic development, including sustainable development, regional rivalry, inequality, fossil-fueled development, and middle-of-the-road development [44]. We used ssp245 and ssp585 as future climate scenarios (2081–2100) to model future distributions of plant species in Qinghai Province. Here, ssp245 differs from ssp585, due to its high CO_2 emissions. Three global circulation models (MIROC-ES2L, MIROC6, MRI-ESM2-0) were selected to capture the two representative concentration pathways (i.e., ssp245 and ssp585). The data on future climate scenarios were averaged based on the above-mentioned models—namely, MIROC-ES2L, MIROC6, and MRI-ESM2-0. In order to reduce over-fitting of the model, a correlation analysis was conducted to calculate the relationships between the 19 bioclimatic variables [45]. Finally, we selected four environmental variables to construct the species distribution model. The environmental variables were bio1 (annual mean temperature), bio4 (temperature seasonality), bio12 (annual precipitation), and bio15 (precipitation seasonality). Terrain data were obtained from (https://www.earthenv.org (accessed on 18 February 2022)). Five variables with a resolution of 10 km—namely elevation, roughness, terrain roughness index

(TRI), vector ruggedness measure (VRM), and terrain position index (TPI)—were selected as terrain data factors. As reliable future projections for topographic factor indices were not available, and including static variables in models alongside dynamic variables can improve model performance [46], we kept these variables static in our projections.

2.4. Species Distribution Model

The maximum entropy model (i.e., Maxent) [36] was used to predict the plant species distribution using only existing species distribution data and environmental variables [45,47], in order to predict the probability and suitability of species distribution in Qinghai Province. The results of the maximum entropy model produced species distribution probability ranging from 0 to 1 [36]. The plant distribution data for Qinghai Province were divided into random training test data (auctrain, 75%) and test data (auctest, 25%) [36]. We ran four replicate runs for each data set for random training test data and test data, and the regulation multiplier was set as 2 [48]; the other parameter took the default values [36,48]. We used a complementary log–log (cloglog) transforms to produce an estimate of the plant species distribution probability, ranging from 0 (lowest) to 1 (highest) [47]. The area under the curve (AUC) and omission rate were used to evaluate the prediction accuracy of the model [45]. AUC was used to evaluate the accuracy of the model, with value ranging from 0 to 1 [45]: the greater the value, the more the species distribution deviates from a random distribution (i.e., AUC = 0.5). The greater the correlation between variables and the model, the higher the accuracy of the model [45]. In this study, the model performance evaluated according to AUC was divided into five discrete categories: failing (0.5–0.6), average (0.6–0.7), good (0.7–0.8), very good (0.8–0.9), and outstanding (0.9–1.0). The greater the correlation between environmental variables and the model, the higher the accuracy of the model. Corresponding to these categories, AUC > 0.7 indicated that the model was effective [45,49]. We used a jackknife method to assess the contribution of environmental variables to the species distribution probability [47]. The output format of the jackknife method showed the contribution rate (%) of environmental variables to plant species distribution probability from 0 to 100%, with 0 representing the smallest contribution and 100% representing the largest [47,50]. We conducted an independent samples *t*-test to assess the significance of differences in the contribution rate (%) of environmental variables to species distribution probability between herbaceous and woody species [51]. Then, we averaged distribution probabilities across all the plant species in Qinghai Province under different climate scenarios (current, ssp245, and ssp585). Finally, we used Tukey tests to compare the species richness differences between woody and herbaceous plants in the nature reserves of Qinghai Province, under the current, ssp245, and ssp585 climate scenarios [52].

2.5. Spatial Conservation Planning

We used the software tool Zonation [53] to determine the PCAs for plant species in Qinghai Province, in order to optimize the protection of plant species in Qinghai Province and limit the reduction of biodiversity in Qinghai Province under future climate change scenarios. We used the distribution probability regarding suitable habitats for each plant species (i.e., the biodiversity feature) as the input to the Zonation software under current, ssp4.5, and ssp8.5 scenarios, respectively. We used the additive benefit function remove rule [54] and set the warp factor to 1, to ensure optimization of the results. Other parameters were set as model default values [54].

We analyzed the vacancy between the PCAs of plant distributions obtained by Zonation and the nature reserve of Qinghai Province and selected a 70% threshold to convert the PCA maps into binary images (i.e., priority and non-PCAs) based on the results obtained by Zonation [55]. The PCAs were assigned a value of 1 with Zonation results higher than 70%, indicating a suitable habitat for plants, and non-PCAs were assigned a value of 0 with the Zonation results lower than 70% [55]. We calculated the grid number count of PCAs inside and outside the nature reserves. In this analysis, the grid number count represents the size of PCAs for plants in the northeastern Qinghai–Tibet Plateau [13]. The percent change (PC) of grid number counts was assessed based on the following equation:

PC = (Af − Ac)/Ac × 100%, where Ac represents the PCAs in current climate scenario, and Af represents the PCAs in future climate scenarios (i.e., ssp4.5 or ssp8.5) [13]. Based on this analysis, the PCAs multiplied by the percentage (%) indicated the percent change in PCAs in nature reserves over time [13].

2.6. Assessing the Ability of Nature Reserves to Protect the Richness of Plants

As is well-known, nature reserves are already divided areas. In order to adapt to climate change, the niches of most species will likely take migration countermeasures and move out of the reserve, offsetting the protection effect of these reserves [56]. In GIS, we combined the PCAs layer with the plant richness layer for Qinghai Province, in order to calculate the mean species richness of woody and herbaceous plants in PCAs in Qinghai Province, as well as the changes in richness of woody and herbaceous plants in priority protected areas in Qinghai Province under different climates [56,57]. The higher the species richness of PCAs in Qinghai Province, the more effort should be made to protect them [56]; that is, the protection of plant richness in nature reserves should be strengthened. Secondly, in GIS, we conducted multi-variate analysis to calculate the distribution probability map for each plant species and, with the intent to guide plant diversity protection in Qinghai Province, analyzed the probability change trends.

3. Results

3.1. Accuracy of the Species Distribution Model

We calculated the AUC and omission rate to evaluate the performance of the model. The average of the training AUC and test AUC for plant species in Qinghai Province were 0.886 and 0.838, respectively, indicating that the model accurately predicted the suitability of plant habitats in Qinghai Province, and the output results of the model were likely very close to the true probability. The average contribution rate of environmental variables to plant distributions in Qinghai Province was heterogenous, but the impact of environmental variables on herbaceous and woody plants in Qinghai Province exhibited almost no difference (Table 1). Among the variables investigated, annual precipitation contributed 29.74% and 30.42% to woody and herbaceous species suitability distributions, respectively, in Qinghai Province. Additionally, the annual mean temperature contributed 21.5% and 21.76% to woody and herbaceous species suitability distributions, respectively, in Qinghai Province (Table 1). Similarly, the contributions of elevation to woody and herbaceous species suitability distributions were 22.75% and 25.06%, respectively. Thus, annual precipitation and annual mean temperature had a greater impact on plant species suitability distributions in Qinghai Province, while the effects of other variables were small (see Table 1).

3.2. Climate Change Impacts on Species Suitability Distributions

Under the current climate scenario, plant species in Qinghai Province were mainly distributed in the southeast of Hainan Tibetan Autonomous Prefecture, Haidong City, Xining City, and Huangnan Tibetan Autonomous Prefecture (Figure 2). We found little difference in the distribution probabilities between woody and herbaceous plant species. Under the influence of future climate scenarios, we observed that the plant distribution in Qinghai Province gradually spread to the northwest, while the distribution probability in the eastern and southern regions also increased significantly (Figure 2). Under the future climate scenarios, concentration pathway ssp585 was associated with wider distributions, relative to ssp245 (Figure 2). These results indicate that climate change will likely promote the expansion of suitable habitat areas for plants in Qinghai Province.

Table 1. Average contributions of environmental variables to the plant species distributions. bio1, annual mean temperature; bio4, temperature seasonality; bio12, annual precipitation; bio15, precipitation seasonality; TPI, terrain position index; TRI, terrain roughness index; VRM, vector ruggedness measure; P indicates the significance of differences in the contribution rate (%) of environmental variables to species distribution probability between herbaceous and woody species, based on independent samples *t*-test.

Avg Contribution	Woody	Herbaceous	*P*
bio1	21.497	21.755	0.902
bio4	7.996	6.926	0.871
bio12	29.741	30.422	0.743
bio15	1.456	2.306	0.166
elevation	22.747	25.058	0.351
roughness	1.987	2.267	0.677
TPI	2.131	2.617	0.353
TRI	4.262	3.021	0.112
VRM	4.252	3.888	0.648

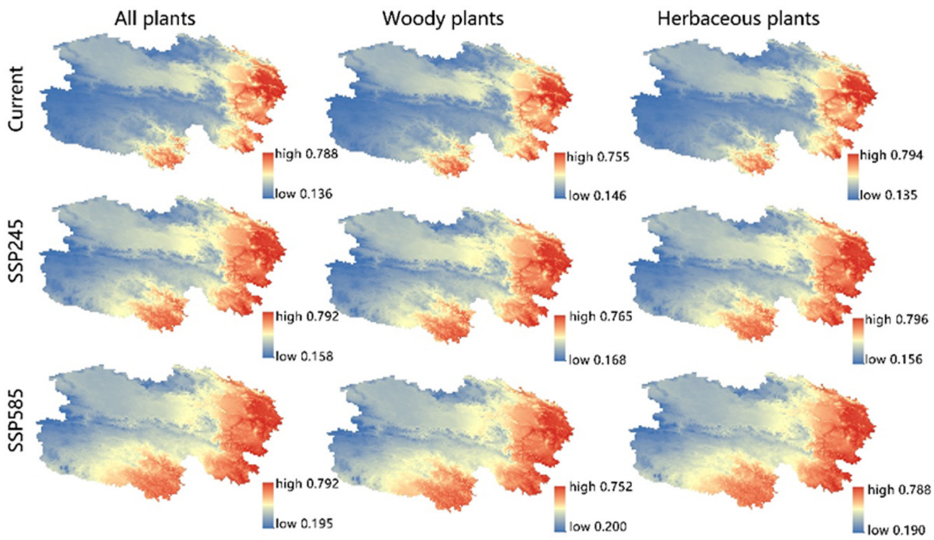

Figure 2. Average distribution probability of plants in Qinghai Province under different climate scenarios (current, ssp245, and ssp585). Red, yellow, and blue represent high, medium, and low probabilities of plant species distributions, respectively.

3.3. Differences in Plant Richness among Various Nature Reserves

We found that the richness of woody and herbaceous plants in the seven nature reserves also increased under climate change scenarios (Figure 3). At the same time, we carried out Tukey's multiple comparison test to compare the nature reserves under the influence of different climate scenarios and analyzed the differences in plant richness among the seven nature reserves. First, we observed that, under the current climate scenario, the richness differences between woody plants and herbaceous plants among the various reserves were consistent (Figure 3); furthermore, under the two future scenarios, the differences and changes of woody plants and herbaceous plants among various reserves remained consistent (Figure 3). Specifically, under the current climate scenario, the plant richness of LB was no different from that of other nature reserves, while the plant richness of KKXL was different from that of other reserves, except LB; however, under climate change scenarios, KKXL and LB also presented differences in plant richness (Figure 3) Second, we also observed that there was no difference in plant richness between QHCDMHAF and SJY under the current climate and ssp245 scenarios, but the difference was significant under ssp585 (Figure 3). Third, there was no difference in plant richness between XHMD and DTBCHYD at any time (Figure 3).

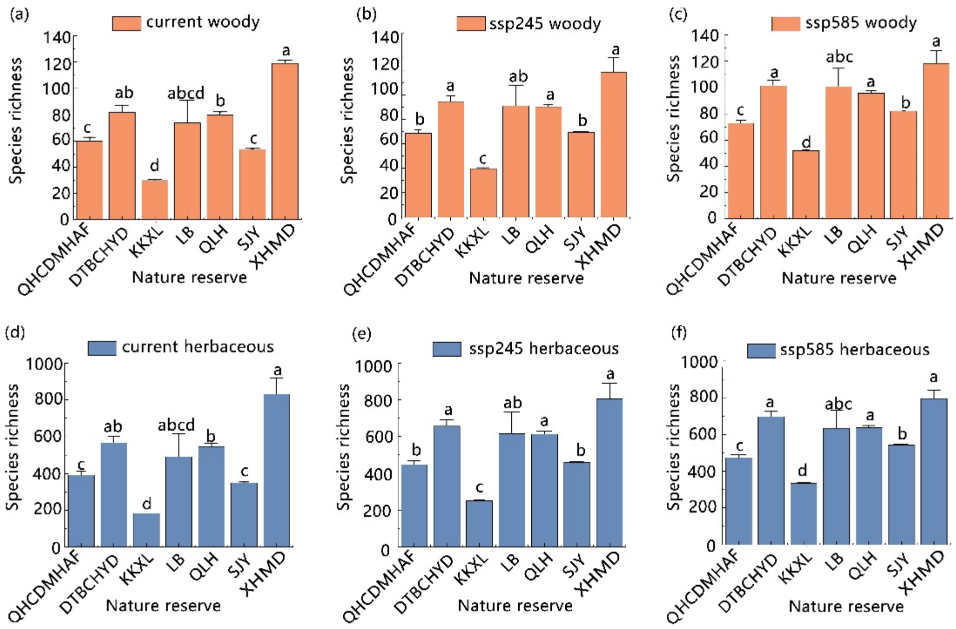

Figure 3. Comparison of the species richness differences between woody and herbaceous plants in the nature reserves of Qinghai Province under current (**a**,**d**), ssp245 (**b**,**e**), and ssp585 (**c**,**f**) climate scenarios, based on Tukey tests. XHMD, Xunhua Mengda National Nature Reserve; DTBCHYD, Datong Beichuan Heyuan District National Nature Reserve; QLH, Qinghai Lake National Nature Reserve; LB, Longbao National Nature Reserve; SJY, Sanjiangyuan National Nature Reserve; QHCDM, Qinghai Chaidamu Haloxylon ammodendron Forest National Nature Reserve; KKXL, Kekexili National Nature Reserve; The a–d are sorted from the largest to the smallest according to the average value. There is a significant difference in the level of not using the same letter to connect.

3.4. PCAs inside and outside Nature Reserves under Climate Change

Based on change from the current climate to the future climate scenarios, we examined the change in PCAs in the nature reserves. The PCAs for plant species in the nature reserves were about three times less than those outside the nature reserves (Table 2). We also found that, within the nature reserves, the PCAs for woody plants continued to increase under the two concentration pathway scenarios in the future, while those for herbaceous plants did not change, compared with the PCAs under climate change (Table 2). In contrast, under ssp585, compared with the current climate, the PCAs were projected to increase by 7.91%, which also indicated that, with the climate change, increased temperatures will promote the PCAs in Qinghai Province (Table 2).

The PCAs for plants were mainly distributed in the eastern and southern regions (Figure 4). We found that, although KKXL is large, there is no suitable place for plants to survive in KKXL, indicating that this reserve has little effect on the protection of plant diversity (Table 2; Figure 4). We also specifically assessed the four reserves QHL, XHMD, DTBCHYD, and LB (Table 2; Figure 4). Under the influence of the change from current to future climate scenarios, the PCAs for plants is not projected to change for these reserves, and all of them are and should retain priority for protection. Thus, these four reserves were projected to be climate change refuges. The PCAs in SJY and QHCDMHA changed obviously in the transition from current to future climate scenarios (Table 2). Specifically, SJY is the largest protected area in Qinghai Province (Figure 1). Under ssp245 and ssp585, the PCAs for woody plants and herbaceous plants in this protected area were projected to increase by 10.43% (Table 2). Under ssp245, there was no change in the PCAs for herbaceous plants, compared with the current climate scenario; however, under ssp585, the PCAs for herbaceous plants were projected to increase by 13.22% (Table 2). The results for the QHCDMHA showed a considerable difference: from the current to future climate scenarios, the PCAs of woody plants were projected to decrease by 13.89%. Under ssp245, the PCAs of herbaceous plants remained unchanged, compared with the current climate scenario (Table 2); however, under ssp585, the PCAs of herbaceous plants in the nature reserves were decreased by 47.22% (Table 2).

Table 2. PCAs (i.e., count number) and predicted change in nature reserves of Qinghai Province under current and future (i.e., ssp245 and ssp585) climate scenarios. W, woody; H, herbaceous; XHMD, Xunhua Mengda National Nature Reserve; DTBCHYD, Datong Beichuan Heyuan District National Nature Reserve; QLH, Qinghai Lake National Nature Reserve; LB, Longbao National Nature Reserve; SJY, Sanjiangyuan National Nature Reserve; QHCDM, Qinghai Chaidamu Haloxylon ammodendron Forest National Nature Reserve; KKXL, Kekexili National Nature Reserve; TCINR, total count in nature reserves; TCONR, total count outside nature reserves.

	PCAs						Change Percentage (CP)			
	Current		ssp245		ssp585		ssp245	ssp245	ssp585	ssp585
Nature reserves	W	H	W	H	W	H	W	H	W	H
XHMD	3	3	3	3	3	3	0.00%	0.00%	0.00%	0.00%
DTBCHYD	17	17	17	17	17	17	0.00%	0.00%	0.00%	0.00%
QLH	88	88	88	88	88	88	0.00%	0.00%	0.00%	0.00%
LB	2	2	2	2	2	2	0.00%	0.00%	0.00%	0.00%
SJY	537	537	593	537	593	608	10.43%	0.00%	10.43%	13.22%
QHCDMHAF	36	36	31	36	31	19	−13.89%	0.00%	−13.89%	−47.22%
KKXL	0	0	0	0	0	0	0.00%	0.00%	0.00%	0.00%
TCINR	683	683	734	683	734	737	7.47%	0.00%	7.47%	7.91%
TCONR	2315	2315	2264	2315	2264	2261	−2.20%	0.00%	−2.20%	−2.33%

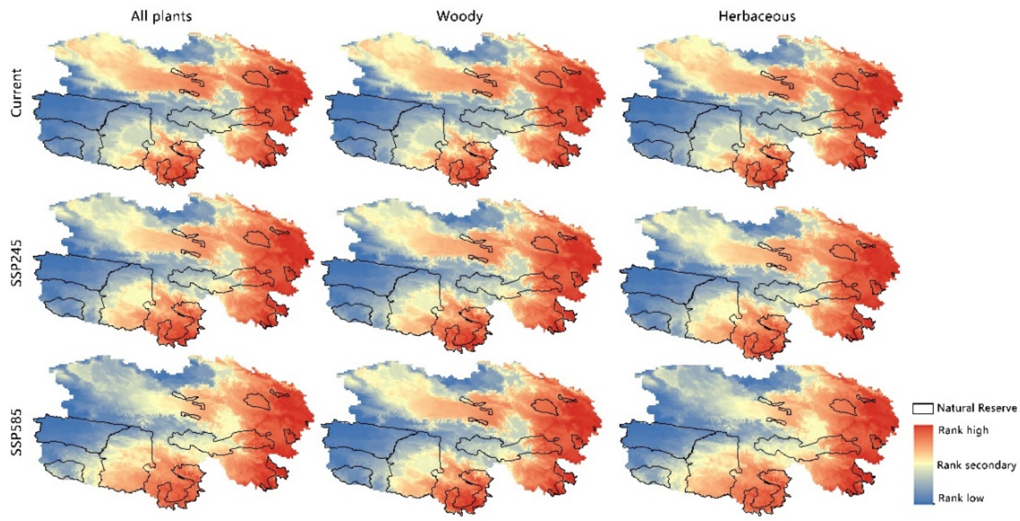

Figure 4. Combined map of PCAs and nature reserves under different climate scenarios (current, ssp245, and ssp585). Red, yellow, and blue indicate high, medium, and low PCAs, respectively.

3.5. Change of Richness in PCAs

Under the current climate, the richness of all species in the PCAs was found to be 542.301, the richness of herbaceous plants was 472.007, and the richness of woody plants was 70.294 (Table 3); under ssp245, the total species richness of plants in the PCAs was 634.909, the richness of herbaceous plants was 552.124, and the richness of woody plants was 82.785 (Table 3); and under ssp585, the total species richness of the PCAs was 704.435, the richness of herbaceous plants was 606.152, and the richness of woody plants was 90.09 (Table 3). We observed that the species richness of both woody plants and herbaceous plants showed an upward trend; in addition, we also found that the richness of herbaceous plants was much higher than that of woody plants (Table 3). According to the distribution probability of each species, we found that the distribution probability of 141 species decreased, the distribution probability of 1060 species increased, and the distribution probability of other species did not change (Table S2).

Table 3. Richness of woody and herbaceous plants in PCAs of Qinghai Province under current and future (i.e., ssp245 and ssp585) climate scenarios.

	Lifestyle	Richness of PCAs
current	Herbaceous	472.007
	Woody	70.294
	All species	542.301
ssp245	Herbaceous	552.124
	woody	82.785
	All species	634.909
ssp585	herbaceous	606.152
	woody	90.090
	All species	696.242

4. Discussion

For plants in the northeastern Qinghai–Tibet Plateau (i.e., Qinghai Province) and other areas globally, climate change may directly or indirectly affect their proliferation and establishment, as well as altering their suitable habitat and environmental impact [23]. In this study, we used species distribution modeling to predict the potential distribution patterns of plant species in Qinghai Province and to assess the potential effects of adaptation and protection strategies under climate change. Our research indicated that annual precipitation and mean annual temperature have the strongest explanatory power for the distribution probability of plant species. Additionally, with the projected increases in temperature and precipitation, the suitable conditions for species are expected to shift [13]. Almost all plants require minimal levels of light, water, and temperature to grow [6,31,58]. In a comparison of the annual mean temperature with the annual precipitation, the contribution rate of annual precipitation to the distribution probability of plant species in Qinghai Province was higher. Over time, compared with the current climate scenario, the probability of plant species distributions under ssp245 was increased under the future climate scenario, while the probability of plant species distributions under ssp585 was further increased, relative to ssp245. Qinghai Province has many glaciers and a high altitude; as temperatures increase, the melting of ice and snow and the thawing of soil is expected to cause the forest line to rise, which will inevitably lead to the continuous expansion of vegetation communities [23,38]. Therefore, at the beginning of the plant growing season, there will be ample water in the soil, which is conducive to the growth of vegetation [59]. Precipitation is the main driving factor of changes in forest ecosystem structure and function, and is an important limiting factor for plant physiological and ecological processes in sparsely vegetated, arid, and semi-arid areas [6,60]. As precipitation increases, soil moisture increases, which is conducive to increasing suitable habitats for plants [6,60]. Therefore, compared with other ecosystems, the vegetation ecosystems in Qinghai Province are more sensitive to precipitation.

Our results showed that the plant species richness in Qinghai Province is mainly concentrated in eastern and southern Qinghai Province. This is because the temperature and precipitation in Qinghai Province decrease from southeast to northwest [38] such that the plant distribution probability is highest in the east and south. In addition, we also found that the seven nature reserves in Qinghai Province are mainly distributed in the southwest of Qinghai Province, with few in the east, indicating that the existing nature reserves cannot play an important role in protecting areas with high plant richness [61,62]. Some studies have also shown that range transfer may contribute to the survival of species, but may also expose them to new biological and abiotic pressures [62]. The inability of a species to adapt to such pressure could cause a collapse of species interactions and threaten the stability and local uniqueness of existing communities, which is of major concern [61,62]. Therefore, in order to cope with the expansion and increase of suitable habitats for plant species in the northwest of Qinghai Province, the natural reserves in this area should be expanded to provide protection for future species distributions.

The range changes caused by climate change may cause suitable niche species to leave nature reserves, thus reducing the relevance of current fixed nature reserves in future conservation strategies based on the assessment of PCAs [5]. Furthermore, we found that plant species richness will increase in PCAs, indicating that the PCA could conserve plants in the northeastern Qinghai–Tibet Plateau. We suspect that the herbaceous plants in Qinghai Chaidamu Haloxylon ammodendron Forest National Nature Reserve may change their niche through plastic responses and evolutionary adaptation, or through tracking of the original climate conditions by migrating, in order to deal with climate change [6,49,63]. There is evidence that, compared with the speed of climate change, the evolution of species climatic niches may be slower [64]. If a species cannot adequately respond to changing abiotic and biological conditions, it may lead to range reductions or local extirpation [64–66]. As most of Qinghai Chaidamu Haloxylon ammodendron Forest National Nature Reserve is desert, the temperature of the reserve is relatively high, which is not suitable for the survival of woody plants and herbaceous plants. Under the influence of the future climate, the temperature will continue to rise, breaking through the tolerance value of plants, and the suitable habitat of plants will change and move out of the reserve [67]. Thus, negative growth of herbaceous and woody plants in the priority conservation area may occur. Although the richness of herbaceous and woody plants in Qinghai Chaidamu Haloxylon ammodendron Forest National Nature Reserve is increasing, the PCAs in the nature reserve are decreasing, which also increases the spatial mismatch between nature reserves and PCAs. Part of the Qinghai Chaidamu Haloxylon ammodendron Forest National Nature Reserve is desert, and the area of desert is gradually increasing with climate change [67]. In addition, the environment is already considered bad, so the PCAs will have little protection effect on this place under future climate scenarios. At this time, we can set the boundary of the nature reserve according to the location of the PCAs, avoiding the waste of protected resources, to a certain extent [68].

With the expected change in climate, the PCAs in Sanjiangyuan National Nature Reserve will increase, while the PCAs of herbaceous plants is significantly greater than that of woody plants. This is because herbaceous plants have strong evolution ability and can continuously adjust their physiological characteristics to temperature changes and migrate to suitable habitats [69]; meanwhile, woody plants have strong tolerance and are relatively less affected by climate [5].

Sanjiangyuan National Nature Reserve is located in the alpine region of the Qinghai Tibet Plateau and is the largest nature reserve in China. Known as the “Chinese water tower,” SJY is rich in vegetation and lakes [29]. The climate alternates between hot and cold seasons and distinct dry and wet seasons [29]. The nature reserves mainly protect typical alpine meadows, alpine grassland vegetation, and species in the family Orchidaceae [29,70]. In Sanjiangyuan National Nature Reserve, herbaceous plants account for a large proportion of species [64]. Its ecosystem is not only very unique, but also very fragile. More than half of Sanjiangyuan National Nature Reserve is composed of key ecosystem types that are very sensitive to climate change [71]. Sanjiangyuan National Nature Reserve is also in one of the regions with the most severe climate change [29]. As such, climate change is expected to have a huge impact on the ecosystem of the reserve [65]. Therefore, we should strengthen the protection of the reserve and focus on the protection of plants in the PCAs.

Kekexili National Nature Reserve mainly exists for the protection of wild animals. It is dominated by small herbs and cushion plants, with few woody plants; these species include *Myricaria prostrata* and *Ephedra gerardiana* [72]. Therefore, under the current and future climate scenarios, climate is expected to have little impact on plants in this nature reserve.

Although the area of Kekexili National Nature Reserve is large, there were no PCAs in this area, which may be due to the different functions associated with establishing the reserve, which mainly protects wildlife resources [72]. Of course, the reserve has little vegetation and generally bad environment, and the future climate will not facilitate the growth of plants. For plants in Longbao National Nature Reserve, Xunhua Mengda National Nature Reserve, Qinghai Lake National Nature Reserve, and Datong Beichuan Heyuan District National Nature Reserve, the PCAs will likely also remain unchanged under climate change scenarios. It should be noted that the areas of these four reserves are limited. In addition, the PCAs outside these four reserves are large, and the plant distribution probabilities in these areas were very high. Therefore, expanding the construction of the nature reserves based on these four original reserves should be considered, such that more plants can be reasonably protected.

The present results indicated that the PCAs inside the nature reserves were too small, while those outside the nature reserves were more than three times higher than those within the reserves. However, the areas outside of nature reserves are basically unprotected, leaving a huge gap in the protection of plant diversity under both current and future climate scenarios. Accordingly, new nature reserves should be established where plant habitats are suitable for the survival of species, in order to provide stable and appropriate habitat areas and to enhance the connectivity between various nature reserves [68]. Each nature reserve should form part of a protection network, in order to enrich plant diversity and improve the ecosystems of Qinghai Province.

Xunhua Mengda National Nature Reserve, Qinghai Lake National Nature Reserve, Datong Beichuan Heyuan District National Nature Reserve, and Longbao National Nature Reserve not only have a large area of priority reserves, but also have high plant richness, consistent with previous studies. According to our results, we found that, under the current climate scenario, there is no difference in plant richness between Longbao National Nature Reserve and other reserves, while there were differences in plant richness between Kekexili National Nature Reserve and the other reserves, except for Longbao National Nature Reserve. However, under the future climate scenarios, a significant difference in plant richness between Longbao National Nature Reserve and Kekexili National Nature Reserve was observed, while there was still no difference between Longbao National Nature Reserve and the other five reserves. The main vegetation types in Longbao National Nature Reserve are meadow and freshwater wetlands [67]. In this reserve, there is plenty of water, and appropriate temperature are conducive to changes in suitable conditions for plants [67]; however, due to the harsh environment and few plants in Kekexili National Nature Reserve [72], the gap between plant richness is gradually widening.

For biodiversity conservation in alpine biodiversity hotspots (e.g., the northeastern Qinghai–Tibet Plateau), conservation efforts should focus on the hotspot network units in eastern and southern Qinghai Province, as most of these areas' present conservation gaps. Under the current and future climate scenarios, Xunhua Mengda National Nature Reserve, Qinghai Lake National Nature Reserve, Datong Beichuan Heyuan District National Nature Reserve, and Longbao National Nature Reserve possess a high degree of biodiversity and are the most suitable reserves for plants. Thus, they can be used as long-term refuges for plant species. We found that the distribution probability of 141 species decreased, the distribution probability of 1060 species increased, and the distribution probability of other species did not change. Based on the Zonation framework [50], the delineated PCAs could maximize the high distribution probability of plant species. Each PCA plays a conservation role for each plant species under climate change. Therefore, if we expand existing nature reserves or add new nature reserves to fill the conservation gap, we not only can protect biodiversity, but may also improve the efficiency of vegetation protection.

With climate change, the richness of woody and herbaceous plants in Qinghai Province showed an increasing trend, and the distribution probability of species also presented an increasing trend. This is not difficult to explain: as Qinghai Province is a mountainous area with low altitude and sparsely populated land, the species niches will migrate to high-altitude areas under climate change [58]. According to the results, the richness of herbaceous plants is much higher than that of woody plants. Qinghai Province, as one of the hotspots of biodiversity, is a cold and high-altitude area. Research has shown that the ultraviolet light incident on mountains is strong [72,73]. As ultraviolet light can inhibit the growth of plant stems, coupled with low temperature, such areas are not conducive to the growth and development of plants [56]. At the same time, if the plants are short, they may facilitate temperature preservation [72,73]. Therefore, the richness of herbaceous plants in Qinghai Province is expected to be higher. In addition, the distribution probability of plant species in Qinghai Province is increasing and the species richness is also rising, indicating that the protection of biodiversity in Qinghai Province is becoming increasingly important, such that the protection demand should be higher. The results indicated that the area of PCAs within the nature reserve was also changing, leading to some differences between the areas of priority protected areas within the nature reserve and those outside the nature reserves; namely, the area of PCAs outside the nature reserve was found to be more than three times that inside the nature reserve, both under current and future scenarios, which indicates that the richness of plant species in most areas of Qinghai Province is still not well-protected. Therefore, we urgently need to expand the protected areas in Qinghai Province, in order to protect plant populations and plant biodiversity in Qinghai Province.

Finally, our study has two limitations, as follows: (1) 162 and 1062 woody and herbaceous plant species were considered, such that the results were biased toward herbaceous plants. However, in alpine regions, the number of woody plant species is always lower than that of herbaceous plants; and (2) we did not include a conservation assessment for each plant species, but instead provided the distribution probability results for each species. Our study indicated that the northeastern Qinghai–Tibet Plateau can provide effective PCA for the conservation of plant species richness under the expected effects of climate change.

5. Conclusions

Under future climate scenarios, the plant richness in Qinghai Province is expected to increase, and the suitable conditions for plants will expand from southeast to northwest. Therefore, climate change will have a significant impact on the conservation efficiency of nature reserves in Qinghai Province. However, in this study, we observed that the PCAs inside and outside the Qinghai nature reserves differed greatly. The area of PCAs outside the nature reserves was more than three times the area of priority protection areas inside the nature reserves. In addition, the protection of plant diversity should focus on the eastern and southern areas of Qinghai Province, and long-term conservation areas and ecological corridors should be established in areas with probability of high priority conservation area and plant species richness. In this study, we systematically assessed the impact of climate on the protection of plant species in Qinghai Province, and the obtained results provide key insights for the protection of alpine regions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/d14110956/s1, Table S1: List of woody and herbaceous plants in Qinghai Province; Table S2: Probability of plant distribution in Qinghai Province under different climate scenarios.

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