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Adaptive Distribution and Vulnerability Assessment of Endangered Maple Species on the Tibetan Plateau

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Abstract: Climate change has had an almost irreversible impact on the distribution patterns of tree species on the Tibetan Plateau, driving some vulnerable species to the brink of extinction. Therefore, it is important to assess the vulnerability of tree species in climate-sensitive areas under the following three IPCC-CMIP6 scenarios: SSP126, SSP370, and SSP585. The MaxEnt model was used to predict adaptive distribution for one endangered (*Acer wardii* W. W. Smith (*A. wardii*)) and six vulnerable maple plants on the Tibetan Plateau under current and future conditions. We then evaluated their vulnerability using the landscape fragmentation index. Our results showed that the current adaptive areas of vulnerable maple species were mainly distributed in the southeast of the Tibetan Plateau. The dominant factors affecting adaptive areas were temperature annual range (BIO7) for *Acer sikkimense* Miq. and *Acer sterculiaceum* Wall.; annual precipitation (BIO12) for *Acer cappadocicum* Gled.; precipitation of driest month (BIO14) for *Acer pectinatum* Wall. ex G. Nicholson, *Acer taronense Hand.*-Mazz., and *A. wardii*; and subsoil clay fraction (S_CLAY) for *Acer campbellii* Hook.f. & Thoms. ex Hiern (*A. campbellii*) Under the three future scenarios, the adaptive areas of maple on the Tibetan Plateau area shifted to the northwest, and habitat suitability increased in the northwestern part of the adaptive areas. In the SSP370 scenario, all seven species showed an increase in adaptive areas, while certain species decreased in some periods under the SSP126 and SSP585 scenarios. The status of the endangered maple species is likely to be even more fragile under the three future scenarios. *A. wardii* and *A. campbellii* are more vulnerable and may face extinction, requiring immediate attention and protection. In contrast, the vulnerability of the remaining five species decreased. In conclusion, this study provides recommendations for conserving vulnerable maple species on the Tibetan Plateau. Our data support understanding the distributional changes and vulnerability assessment of these tree species.

Keywords: climate change; MaxEnt model; vulnerable maple species; adaptive distribution; vulnerability assessment

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1. Introduction

Climate change is one of the most important factors affecting the distribution and shifts in adaptive areas for vulnerable species [1,2]. Climate change not only affects the growth of plants [3,4] but also significantly influences their geographic distribution patterns [5,6], thereby directly or indirectly affecting biodiversity [7,8]. The distribution patterns of species have thus become a focus of global concern [9,10], especially in the context of global warming [11]. The Tibetan Plateau, recognized as a sensitive and ecologically vulnerable zone to climate change [12–14], has a unique geographical location and special ecological environment that promotes the diversity and richness of species [15–17]. Climate warming will likely lead to the gradual migration of vulnerable species to higher altitudes and the destruction of and reduction in adaptive areas, and may even lead to extinction for certain species, which presents obstacles to the implementation of conservation measures [18–26]. Therefore, exploring the responses of vulnerable species' adaptive distribution (suitable areas) and vulnerability to climate change improves the development of scientific conservation strategies [27].

Predicting the adaptive geographic distribution of species under climate change scenarios is a common method for understanding species adaptation [28]. Currently, species distribution models (SDMs) are a popular approach to predicting the adaptive geographical ranges of species, using data on the geographical distribution of species, bioclimatic and environmental factors, and other relevant information [29,30]. As a commonly used ecological niche model [31], the maximum entropy model (MaxEnt) has attracted more attention due to its relatively superior predictive power [32–35]. The MaxEnt model outperforms other modeling approaches, such as genetic algorithms for Rule-Set Prediction (GARP), Ecological Niche Factor Analysis (ENFA), BIOCLIM, and DOMAIN [36]. Most importantly, the MaxEnt method provides species response curves for environmental parameters; additionally, it is insensitive to sample sizes [37], even ones as small as three to five [36,38–40]. The MaxEnt model has been widely used to simulate the adaptive distribution areas of various types of vegetation in the context of climate change [41], such as violet crops in China [42,43], as well as vulnerable species [44,45].

The maple (*Acer*) genus has about 150 species in China, and it is an important component of temperate deciduous broad-leaved forests, with the eastern–southern Tibetan Plateau as one of its natural distribution ranges [46–48]. It plays an irreplaceable role in maintaining the ecological environment and water resources, and has an important influence on biodiversity in the Tibetan Plateau [49,50]. According to an assessment of maple on the Tibetan Plateau by the China Red List Species [51], *Acer wardii* W. W. Smith (*A. wardii*) was listed as Endangered (EN); *Acer campbellii* Hook.f. & Thoms. ex Hiern (*A. campbellii*), *Acer cappadocicum* Gled. (*A. cappadocicum*), *Acer pectinatum* Wall. ex G. Nicholson (*A. pectinatum*), *Acer sikkimense* Miq. (*A. sikkimense*), *Acer sterculiaceum* Wall. (*A. sterculiaceum*), and *Acer taronense Hand*.-Mazz. (*A. taronense*) were all listed as Vulnerable (VU). In recent decades, extensive studies have focused on the genetic breeding, vegetation classification, and medicinal purposes of these maple species [52–57]. Although some studies have analyzed the factors that influence the geographical distribution and migration direction of maple [58,59], there are very few high-quality studies regarding the variations in its adaptive distribution and vulnerability assessments on the Tibetan Plateau.

In this study, we used the MaxEnt model to analyze the adaptive areas of maple species on the Tibetan Plateau, based on the geographical distribution of vegetation data and climate, topography, and soil factors. We then evaluated their vulnerability to climate change using the landscape fragmentation index. This research aims to (1) identify and analyze the dominant environmental factors limiting the distribution of maple species on the Tibetan Plateau; (2) simulate and predict the adaptive areas of maple species on the Tibetan Plateau under different scenarios and at different times; and (3) assess the vulnerability of maple species in various regions of the Tibetan Plateau under different scenarios and at different times in the future. Our study offers invaluable insights for the scientific management of and conservation strategies for maple species under the impacts of climate change.

2. Materials and Methods

2.1. Data Screening and Processing

Tibetan Plateau boundary data were obtained from the National Tibetan Plateau Science Data Centre [60]. Provincial boundary data were obtained from the Centre for Resource and Environmental Science and Data of the Chinese Academy of Sciences [61].

Geographical distribution data for the seven maple species were obtained from two sources: (1) the Global Biodiversity Information Network Database [62]; (2) the China Digital Herbarium [63]. Firstly, invalid, duplicated, and cultivated data were removed from the GBIF and CVH databases; then, longitude and latitude were determined according to the geographical location of the species. Secondly, the ArcGIS 10.8 SDM tool was used to set a buffer for a 5 km × 5 km (2.5′) grid. Only one distribution point remained in each grid. Finally, we collected a total of 158 distribution points for the seven maple samples (Figure 1). To build the MaxEnt model, we inputted the information collected on species distribution points into Excel and saved it in a separate CSV format.

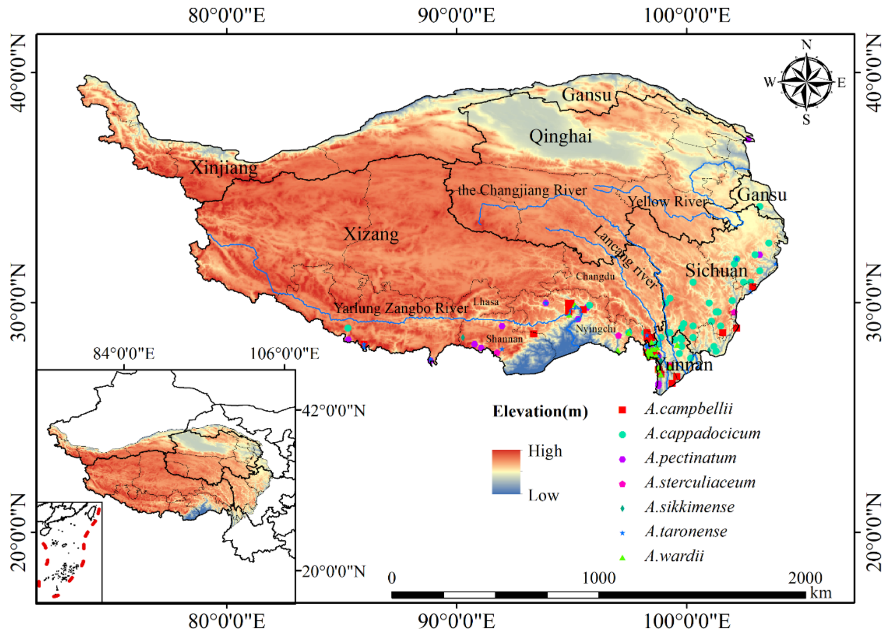

Figure 1. The distribution of maple on the Tibetan Plateau.

A total of 36 environmental factors (including 19 bioclimate factors, 3 topography factors, and 14 soil factors) were chosen. In the IPCC-CMIP6, four shared socio-economic paths (SSPs) are set up in future climate scenarios (SSP126, SSP245, SSP370, and SSP585) [64]. In many studies, it is very common and representative to select three future climate models (SSP126, SSP370, and SSP585), with low, medium, and high forcing [65,66]. SSP126 represents a sustainable scenario with the lowest radiative forcing, as well as low mitigation and adaptation challenges [67]. SSP370 represents the medium-to-high end of the range of future forcing pathways, with particularly high aerosol emissions and land use change [67]. SSP585 represents the highest radiative forcing scenario, with many socio-economic challenges to mitigation and few to adaptation [67,68]. Therefore, selecting these three representative climate scenarios can enhance the scientific accuracy of the research results [69]. Three scenarios (SSP126, SSP370, and SSP585) under the BCC-CSM2-MR model were selected in this study. Current (1970–2000) and future climate (2050s (2041–2060), 2070s (2061–2080), and 2090s (2081–2100)) data and topography data were downloaded from the World Climate Database [70]. Soil data were obtained from the World Soil Database [71]. The spatial resolution of the above data was resampled to 2.5′ via ArcGIS 10.8 for subsequent research analysis. For this study, we assumed that topography and soil factors would remain unchanged over the next 100 years, as climate change scenarios are not expected to have a significant impact on these factors.

We eliminated some factors because of strong correlations with other factors to avoid model overfitting as follows. Firstly, 36 environmental factors were imported into the MaxEnt software (version 3.4.4) for simulation. Factors with a percentage contribution of >1.0% were screened to obtain the corresponding environmental factors. Secondly, environmental factors were extracted according to the distribution points of species' coordinate information using ArcGIS 10.8 software, and Pearson correlation coefficients were calculated using IBM SPSS 27 software for correlation analysis. If two or more of the screened environmental variables have a correlation with an absolute value of ≥0.8 [21,65], only the factor with the largest contribution was selected. Finally, we constructed models using the screened environmental factors (Table 1).

Table 1. Environmental factors involved in species modeling.

Category	Variable	*A. campbellii*	*A. pectinatum*	*A. pectinatum*	*A. sikkimense*	*A. sterculiaceum*	*A. taronense*	*A. wardii*
Climate	BIO2	√	√	√	-	√	-	√
	BIO3	-	√	√	-	-	√	-
	BIO4	√	√	-	-	√	√	√
	BIO5	-	√	-	-	-	-	-
	BIO6	-	√	-	-	-	-	-
	BIO7	√	-	√	√	√	√	-
	BIO11	-	-	√	√	-	√	-
	BIO12	√	√	-	-	-	-	√
	BIO14	√	-	√	-	-	√	√
	BIO15	-	√	√	-	-	-	-
	BIO16	-	-	-	-	√	-	-
	BIO17	-	-	-	-	√	-	-
Topography	SLO	√	√	√	-	-	√	√
	ASP	√	√	√	-	-	√	√
Soil	T_ESP	-	√	√	-	-	√	√
	T_GRAVEL	√	-	√	-	√	-	√
	T_PH_H_2O	-	-	-	-	√	-	-
	T_REF_ BULK_DEN	-	-	-	-	√	-	-
	S_CLAY	√	√	√	-	-	√	√
	S_GRAVEL	√	-	-	√	-	-	-
	S_REF_ BULK_DEN	-	-	-	√	√	-	-

See Table S1 for an explanation according to environmental variable; ticks indicate modelling factor.

2.2. Model Prediction and Accuracy Assessment

Species distribution data and environmental factors were imported into MaxEnt 3.4.4, and the samples were tested using the cross-validation method. A total of 75% of the distribution point data were randomly selected to build the model as the training group, and the remaining 25% of the distribution data were selected to test the accuracy of the model as the test group. The output data format was logistic, and the process was repeated 10 times. We tested the accuracy of the model predictions based on the closed area under the curve (AUC) value formed by the receiver operator characteristic curves (ROCs) and the horizontal coordinates [72]. The AUC value is in the ranges [0, 1]. The higher the AUC value is, the more accurate the model is. A value in the range [0.9, 1] indicates a perfect prediction [73]. The jackknife test can be used to evaluate the impact of environmental variables on the model. The most significant factor is determined using the environmental variable with the greatest contribution.

The output of the MaxEnt result was the Habitat Suitability Index (HSI) [74] on species distribution, representing the probability of species occurrence. Due to the different ecological characteristics of different species, there was no fixed format for classifying the adaptive distribution for species prediction results. Thus, we chose a method commonly used by researchers, the Natural Breaks (Jenks) classification method [21]. Typically, MaxEnt predictions are classified into four categories (Table S2), namely, not adaptive, minimally adaptive, moderately adaptive, and highly adaptive, and the area of adaptive areas was quantified.

2.3. Habitat Suitability Calculation Methodologies for Highly Adaptive Areas

We applied the equation $S_1 = (FR - SR)/(FR + SR)$ to the analysis of changes in highly adaptive areas over the next three periods and three scenarios. The study produced a range of values from −1 to 1, indicating a decrease or increase in habitat suitability, respectively. S1 represents the trend of changes in highly adaptive areas under future climate change. SR and FR represent the HIS value of each raster in the present and future, respectively [75,76].

2.4. Vulnerability Assessment Methodologies for Highly Adaptive Areas

Landscape pattern indices can flexibly reflect information on landscape patterns, revealing their structural and spatial configuration characteristics [77]. Patch density (PD) is a fundamental index that represents landscape configuration. It indicates the number of patches per unit area within an area. PD describes the best indicator of landscape fragmentation, and landscapes with a higher density of patch types are more fragmented [78]. It has been shown that the negative effects of habitat fragmentation on plant populations are common phenomena, often being the main cause of local species extinction [79]. Thus, we used fragmentation to assess the vulnerability of species. We first used FragStats 4.2 software to compute the number of patches (NPs) in the landscape pattern of highly adaptive areas. Then, the formula PD = NP/A was applied to calculate the density of patches in high-suitability areas for the three scenarios in the next three periods, where PD is the density of highly adaptive area patches, NP is the number of highly adaptive area patches, and A is the area of highly adaptive areas.

3. Results

3.1. Current Adaptive Distribution and Environmental Factors

Most of the adaptive areas for the seven vulnerable maple species are found in the southeastern part of the Tibetan Plateau (Yunnan, Sichuan, and Tibet), with a few adaptive areas in the southwestern part. The adaptive areas for each species overlap, with the highly adaptive areas mainly distributed in Yunnan (Figure 2). The adaptive areas of *A. cappadocicum* and *A. pectinatum* are the largest (12.41% and 12.38% of the Tibetan Plateau). *A. sikkimense* has the largest highly adaptive area (2.9% of the Tibetan Plateau), while *A. wardii* has the smallest area for both adaptive and highly adaptive areas (only 3.78% and 0.31% of the Tibetan Plateau; Table S4). The dominant factors of seven vulnerable maple species include *A. cappadocicum* (BIO12, 36.7%), *A. sikkimense* (BIO7, 53.9%), *A. sterculiaceum* (BIO7, 40.6%), *A. pectinatum* (BIO14, 47.7%), *A. taronense* (BIO14, 53%), *A. wardii* (BIO14, 64.5%), and *A. campbellii* (S_CLAY, 29.3%) (Figure S1).

3.2. Future Adaptive Distribution

We conducted an analysis of future changes in the distribution of the seven maple species under different scenarios based on current patterns. The habitats for the seven maple species in each period scenario are predominantly in the southeastern part of the Tibetan Plateau (Yunnan, Sichuan, and Xizang), with a concentration in southeastern Tibet (Nyingchi and Chamdo) and a migration to the northwestern part of the plateau, with high latitudes or high altitudes. *A. cappadocicum*, *A. pectinatum*, *A. sikkimense*, and *A. taronense* showed significant migration trends, while the remaining three species showed small changes in their habitats and relatively insignificant migration trends (Figures 2–5).

In the 2050s, for the SSP126 scenario, *A. taronense* had the largest adaptive areas, while in the SSP370 scenario, the remaining six plants had the largest adaptive areas. In the SSP370 scenario, *A. campbellii*'s adaptive areas increased, while they decreased in the other two scenarios. The remaining six plants' adaptive areas increased to varying degrees in all three scenarios (Figure 3 and Table S5). Under SSP126 and SSP370 scenarios, *A. campbellii* had a larger area of reduced habitat suitability, while *A. sikkimense* had a larger area of reduced habitat suitability under all scenarios (Figure S3).

In the 2070s, for the SSP126 scenario, the largest adaptive areas were found for *A. sterculiaceum*, while in the SSP370 scenario, *A. campbellii* and *A. wardii* had the largest adaptive areas. The remaining four plants had their largest adaptive areas in the SSP585 scenario. Notably, the largest highly adaptive areas for the seven plants were observed in the SSP370 scenario. In the SSP126 scenario, *A. wardii*'s adaptive areas increased, while they decreased in the other two scenarios. The remaining six plants' adaptive areas increased to varying degrees in all three scenarios (Figure 4 and Table S5). In all three scenarios, the adaptive areas of *A. sikkimense*, *A. campbellii*, and *A. wardii* experienced a greater decline in habitat suitability. Similarly, in the SSP126 and SSP370 scenarios, the adaptive areas of *A. pectinatum* and *A. taronense* also showed a decline, being greater in terms of habitat suitability (Figure S4).

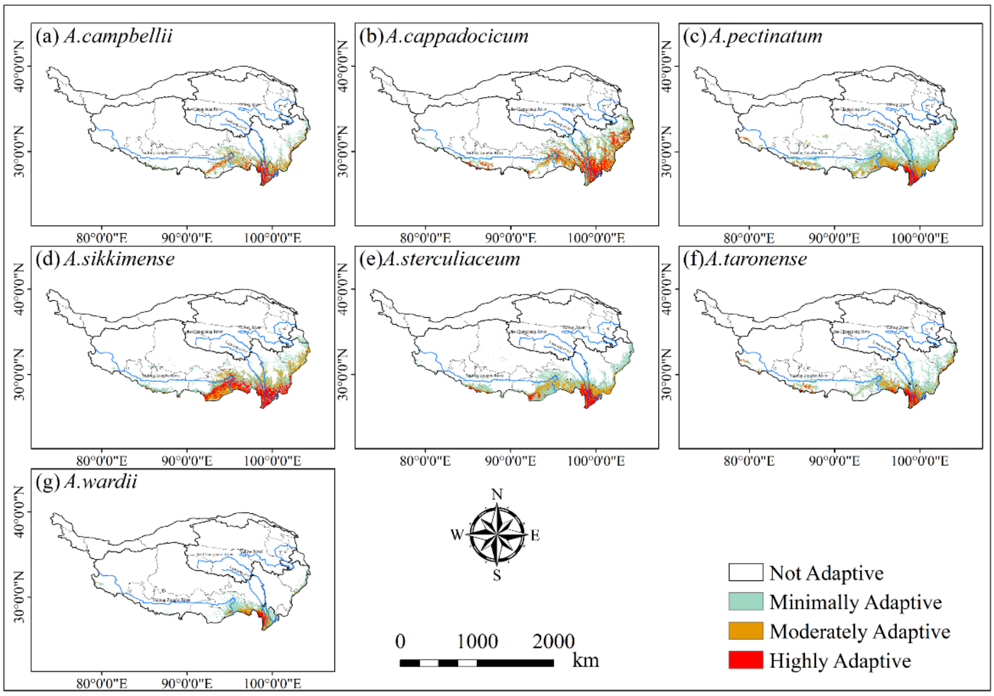

Figure 2. Adaptive distribution of seven maple species under the current climate.

In the 2090s, for the SSP370 scenario, the largest adaptive areas were observed for *A. campbellii*, *A. cappadocicum*, *A. sterculiaceum*, and *A. wardii*. In the SSP585 scenario, the largest adaptive areas were observed for the remaining three maple species. It is worth noting that the SSP370 scenario had the largest adaptive areas for the seven plants. In the SSP126 scenario, the adaptive areas of *A. wardii* decreased, while in the other two scenarios, they increased. The remaining six plants exhibited an increase in adaptive areas under all three scenarios, although to varying degrees (Figure 5 and Table S5). Reductions in habitat suitability were greater in all three scenarios for *A. sikkimense*, and for the remaining six species, these reductions were greater in the SSP126 scenario (Figure S5).

3.3. Vulnerability Assessment of Maple

In the current condition, *A. campbellii* (61.41) exhibited the highest vulnerability, while *A. sikkimense* (10.71) exhibited the lowest. *A. cappadocicum*, *A. taronense*, and *A. wardii* exhibited similar vulnerability levels, being relatively small (Figure 6a). In the 2050s, *A. campbellii* (66.97, 68.12, and 51.60) exhibited the highest vulnerability in highly adaptive areas across all three scenarios, while *A. sikkimense* (16.98, 11.30, and 12.44) exhibited the lowest (Figure 6b). In the 2070s, *A. campbellii* (88.23) exhibited the highest vulnerability in highly adaptive areas in the SSP585 scenario, while *A. wardii* (68.25 and 97.92) had the highest vulnerability in the remaining two scenarios. *A. sikkimense* (11.16, 12.06, and 14.41), however, had the lowest vulnerability in highly adaptive areas across all three scenarios (Figure 6c). In the 2090s, vulnerability in the highly adaptive areas was highest for *A. wardii* (125.84) under the SSP126 scenario, while it was highest for *A. campbellii* in the remaining two scenarios (67.99 and 66.26). In the SSP585 scenario, *A. sterculiaceum* (21.00) exhibited the lowest vulnerability in highly adaptive areas, similarly to *A. sikkimense* in the remaining two scenarios (14.36 and 20.49; Figure 6d).

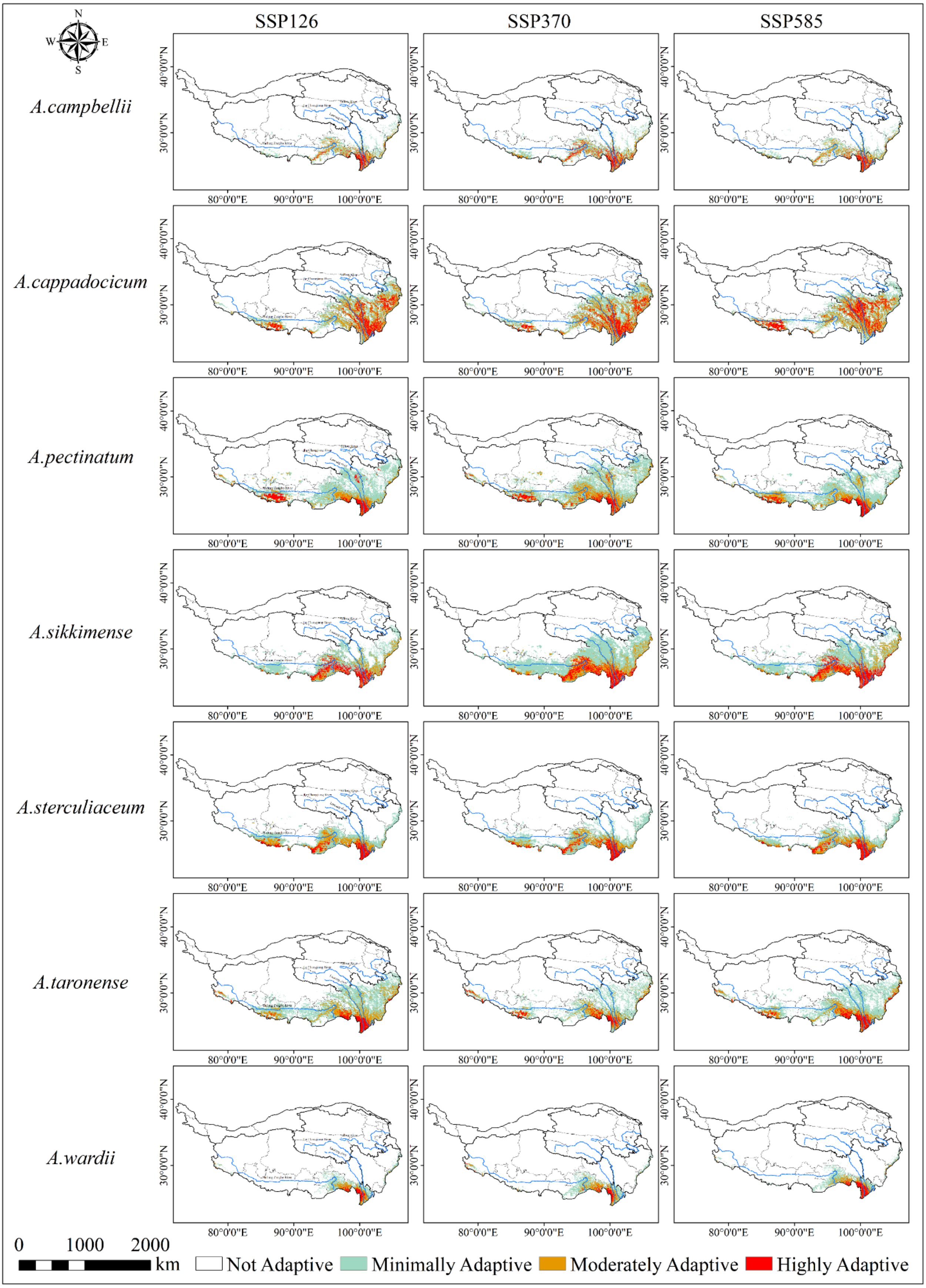

Figure 3. Spatial adaptive distribution of the seven maple species under three scenarios (SSP126, SSP370, and SSP585) in the 2050s.

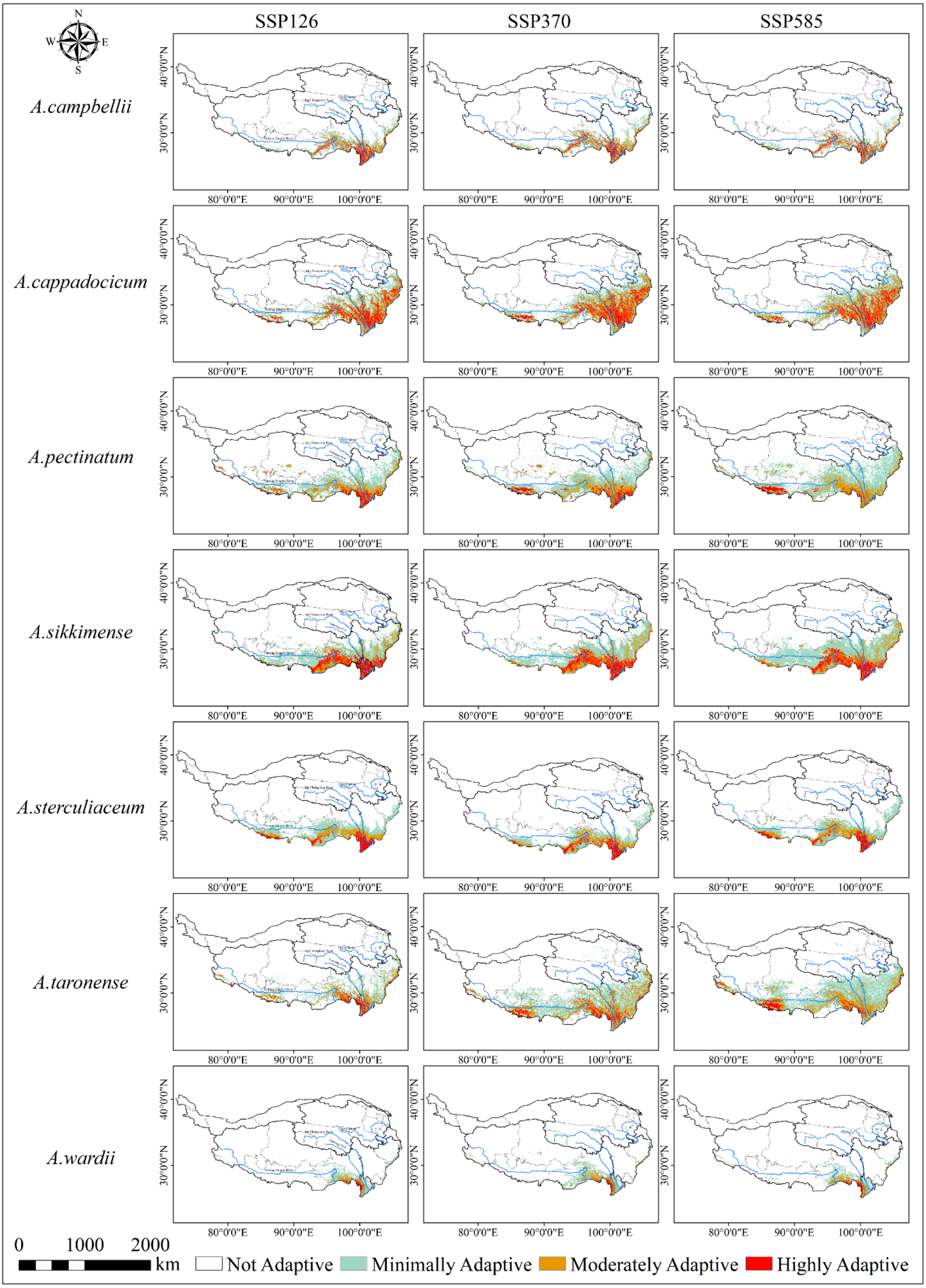

Figure 4. Spatial adaptive distribution of the seven maple species under three scenarios (SSP126, SSP370, and SSP585) in the 2070s.

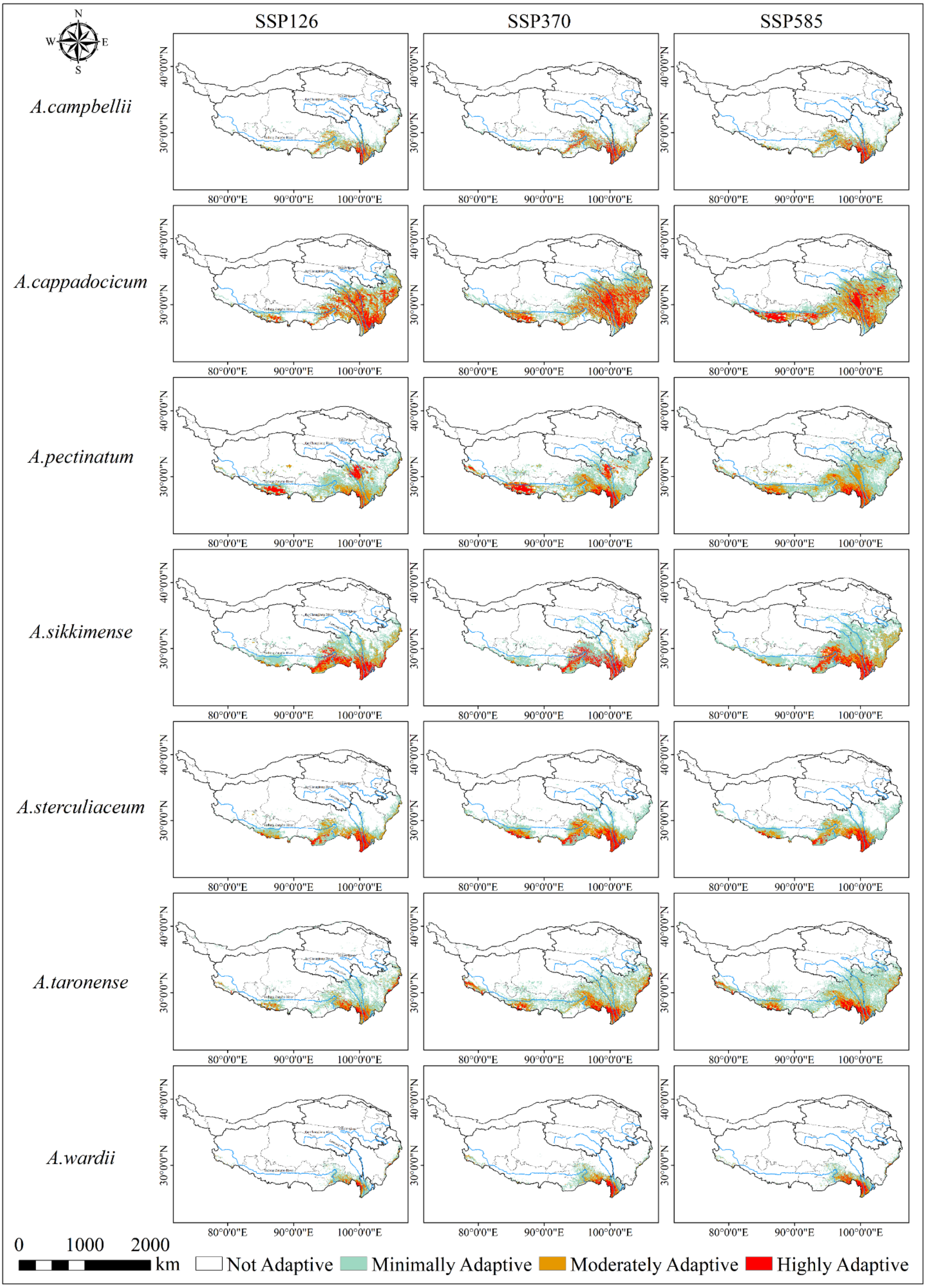

Figure 5. Spatial adaptive distribution of the seven maple species under three scenarios (SSP126, SSP370, and SSP585) in the 2090s.

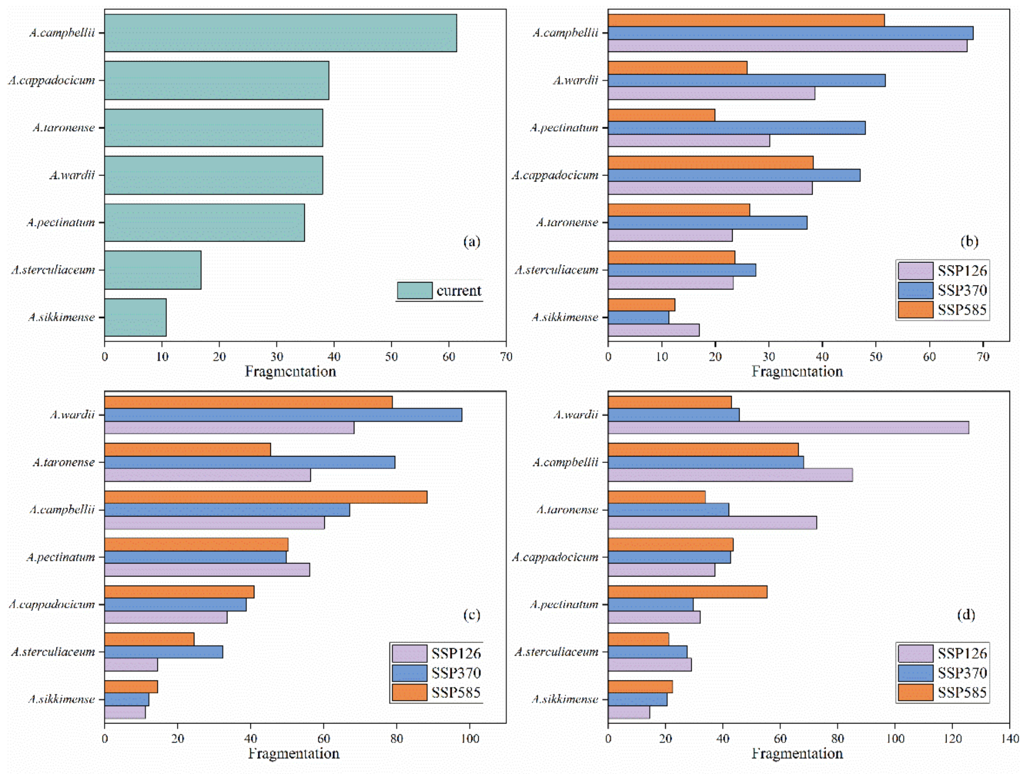

Figure 6. Fragmentation (PCS/10^6 ha) of the highly adaptive areas for the seven maple species across current and future (three) scenarios. (**a**) Current, (**b**) 2050s, (**c**) 2070s, (**d**) 2090s.

4. Discussion

The prediction accuracy of the MaxEnt model depends on the actual distribution points of species and environmental factors [80]. Obtaining accurate and reliable distribution points for endangered species can be challenging due to factors including small populations, the topography of the Tibetan Plateau, and poor accessibility, potentially affecting the simulation results. However, the results (Figure S2) obtained from the MaxEnt model showed that the AUC values obtained from the means of the training set for the seven maple species were both close to 1 (Table S3), indicating that the results were highly accurate. Thus, the MaxEnt model can be used to simulate the adaptive distribution of endangered maple plants on the Tibetan Plateau [72,73].

There are numerous factors that influence the geographical distribution of plants, and previous studies have found that climate is a key factor influencing the distribution of plants at the regional scale [81–83]. The adaptive areas of the seven maple species are mainly distributed in the southeastern part of the Tibetan Plateau, characterized by a cold and moist climate influenced by humid air from the Indian Ocean [58]. These areas represent conditions that are conducive to the survival of these maple species [84]. Many studies have also been conducted on the response of Tibetan Plateau vegetation to climatic factors. The high contribution of precipitation (BIO12, BIO14) to species distribution models has been noted in studies of maple [58,85,86], which is consistent with our study including *A. cappadocicum*, *A. pectinatum*, *A. taronense*, and *A. wardii.* When studying the dominant environmental factors that influence vegetation change on the Tibetan Plateau, the effect of soil moisture was found to be more pronounced relative to precipitation [87], which is consistent with our study on *A. campbellii.*

On the Tibetan Plateau, precipitation was found to play a dominant role in the distribution of vegetation growth over a significantly larger area when compared to temperature [88]; that is, vegetation change is more closely influenced by precipitation than by temperature [89]. Moreover, the distribution of vegetation growth was also found to be driven by hydrothermal factors in more than 50% of the area, with air temperature being the primary driver [90]. Nepal is adjacent to the Tibetan Plateau, and temperature (BIO7) was found to be a key determinant in species distribution in a study of its important plant species [91], which is consistent with our study including *A. sikkimense* and *A. sterculiaceum.* However, the results obtained vary due to differences in the data used by the researchers, the study period, the study area, and the method of analysis. Based on the different physiological and ecological characteristics of maple on the Tibetan Plateau, we concluded that changes in temperature and precipitation are the main drivers of change in the geographical distribution of vegetation influenced by climate change [92].

The distribution of vegetation on the Tibetan Plateau was modeled using BIOME3 under the scenarios of future climate change and elevated CO_2 levels, and the vegetation zone was found to shift toward the northwest [93]. The forests on the Tibetan Plateau will expand in a north-westerly direction as a result of warmer temperatures, with the vegetation boundary moving northwest when the climate warms by 1.5 °C. This trend is likely to strengthen with increased levels of precipitation [94]. *Picea likiangensis* and *Picea purpurea* on the Tibetan Plateau have been projected to increase their range to the northwest under future climate change scenarios [95]. As the eastern part of the Tibetan Plateau shows a wetter trend, accompanied by warmer temperatures, this may limit the eastward expansion of plateau vegetation [96]. Climate change may cause species to shift from low to high elevations [97], and existing studies have found that most species will migrate and expand to higher altitudes and latitudes under future warming trends [21,98]. Although the distribution pattern of species varies under different scenarios, areas with higher biodiversity and habitat suitability are mainly located in the southern part of the Tibetan Plateau. As such, most of these species will migrate to the northwest in the future [99,100]. This aligns with the direction of migration and expansion of the seven maple habitats identified within this study across various future scenarios.

The range of appropriate plant habitats is both increasing and contracting due to the impact of global climate change. For example, simulations using the revised LPJ dynamic model found that the geographic distribution of Tibetan Plateau forests and shrub vegetation will increase in the future [101]. Global warming contributes to wet weather in some parts of the plateau, which favors the growth of vegetation and an increase in vegetation cover [102]. As a result, the rejuvenation period of the vegetation in the plateau region has generally advanced, resulting in increased vegetation cover [89,103]. In addition, broadleaf forests have increased over a large area [94], which has played a significant positive role in the trend of Net Primary Productivity (NPP) across the plateau [104,105]. All of the above studies indicate that Tibetan Plateau climate change has a positive effect on the expansion of adaptive areas in plateau ecosystems, which is consistent with the results of the present study. Other studies have found that climate change will negatively impact plant species and ecosystems [106,107]. The decline in the size of adaptive areas in some scenarios can also be explained by the trends identified in this study for *A. wardii* and *A. campbellii*.

Species vulnerability is commonly evaluated by comparing potential changes in their ranges [108]. This study found that the adaptive areas for all seven maple species increased in all three periods under the SSP370 scenario. The changes in adaptive areas and highly adaptive areas were comprehensively analyzed for the remaining two scenarios. The SSP370 scenario was found to be the most favorable for the survival of vulnerable maple vegetation in the Tibetan Plateau compared to the other two scenarios. Habitat and climate change can significantly hinder plant conservation [109]. Habitat loss and fragmentation pose significant threats to various species [110]. Due to climate change, the adaptive and highly adaptive areas for the endangered species *A. wardii* are the smallest. Thus, it is the most vulnerable species. Consequently, it is highly likely that this species will become extinct in the future. There has been a decrease in the adaptive areas for *A. campbellii*, and its vulnerability has increased. In the SSP585 scenario, its vulnerability was higher than that of the endangered *A. wardii* in the three time periods. This suggests that *A. campbellii* is likely to become an endangered species or even face extinction in the future. These species require immediate as well as focused attention and protection. *A. sikkimense* and *A. sterculiaceum* are less vulnerable than the other species, exhibiting increased adaptive areas, which suggests a very high likelihood of a future conservation downgrade to non-threatened status. In the vast majority of cases, the vulnerability of the remaining three species was lower than that of *A. wardii*. This indicates that there is a low probability of these species becoming endangered in the future, as well as a high probability of them being classified as near-threatened or even non-threatened. The results of this study indicate an increase in species vulnerability and a significant decline in habitat suitability under different future scenarios [111]. The corroboration between the two results indicates the accuracy of the results from the vulnerability assessment.

To mitigate the unavoidable impacts of climate change on plants [85], effective conservation strategies should be adopted in a timely manner. Nature reserves play a crucial role in protecting and restoring vulnerable vegetation [112]. We suggest that the spatial pattern of nature reserves should be optimized and adjusted by considering the distribution and physiological characteristics of various species, as well as the existing nature reserves. This would facilitate establishing a system of nature reserves with national park clusters as the main body, similarly to Yellowstone National Park. The management and protection of endangered maple species' germplasm resources and their habitats should be strengthened in protected areas. This could include the establishment of a modern ex vivo preserved gene bank and the development of sustainable land use planning. In situ conservation should be carried out in areas with stable habitats. For habitats unsuitable for vegetation growth, relocation conservation can be utilized by combining the physiological characteristics of maple and transplanting them to suitable adaptive areas at high altitudes and latitudes [113].

5. Conclusions

Maple is an important component of temperate deciduous broad-leaved forests, playing an irreplaceable role in maintaining the ecological environment and water resources on the Tibetan Plateau. The MaxEnt model was used to predict adaptive distribution for maple plants on the Tibetan Plateau under current and three future scenarios (SSP126, SSP370, and SSP585). We then evaluated their vulnerability using the landscape fragmentation index and proposed feasible conservation recommendations. We observed the following: (1) In all three current and future scenarios, vulnerable maple plants were mainly located in the southeastern part of the Tibetan Plateau. (2) Vulnerable maple species in the Tibetan Plateau were subject to the combined effects of temperature and precipitation. The most important factor for the distribution of *Acer cappadocicum* Gled., *Acer pectinatum* Wall., *Acer taronense* Hand., and *Acer wardii* was precipitation, while the distribution of *Acer sikkimense* Miq. and *Acer sterculiaceum* Wall. was more dependent on changes in temperature. However, the dominant factor was subsoil clay fraction (S_CLAY) for *Acer campbellii* Hook. (3) In all three future scenarios, adaptive areas migrate northwest toward higher altitudes and latitudes. The SSP370 scenario indicated an increase in adaptive areas for all seven vulnerable maple plant species in the Tibetan Plateau. Conversely, the remaining two scenarios demonstrated a decrease in adaptive areas for some species. (4) A future vulnerability assessment of maple species on the Tibetan Plateau found that *Acer wardii* is highly likely to become extinct, and *Acer campbellii* Hook. is highly likely to become endangered or even extinct under the future three scenarios. *Acer sikkimense* Miq. and *Acer sterculiaceum* Wall. are highly likely to be non-threatened, while the remaining three species are likely to be near threatened or even non-threatened. (5) We recommend efforts targeted toward the conservation of vulnerable maple species in the Tibetan Plateau region. This study provides data that support understanding distributional changes and vulnerability assessment of maple species on the Tibetan Plateau.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f15030491/s1, Figure S1. Contribution of environmental factors for the seven maple species: (a) *A. campbellii*, (b) *A. cappadocicum*, (c) *A. pectinatum*, (d) *A. sikkimense*, (e) *A. sterculiaceum*, (f) *A. taronense*, and (g) *A. wardii*. Figure S2. AUC training values for the seven maple species: (a) *A. campbellii*, (b) *A. cappadocicum*, (c) *A. pectinatum*, (d) *A. sikkimense*, (e) *A. sterculiaceum*, (f) *A. taronense*, and (g) *A. wardii*. Figure S3. Trends in highly adaptive areas for maple under different scenarios in the 2050s. Figure S4. Trends in highly adaptive areas for maple under different scenarios in the 2070s. Figure S5. Trends in highly adaptive areas for maple under different scenarios in the 2090s. Table S1. Environmental factors used for modeling. Table S2. Classification criteria for vulnerable maple species. Table S3. AUC values of 7 species of maple vegetation. Table S4. Adaptive areas ($\times 10^4$ km^2) of 7 maple species in contemporary climate. Table S5. Adaptive areas ($\times 10^4$ km^2) of 7 maple species in future climate scenario.

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