diversity

MDPI

Article

Climate Change-Driven Projections of Suitable Habitat for *Phleum pratense* Across China

Jing Pang [1,2], Na He [3,*], Chunjuan Shi [1], Guangtao Meng [2,3], Qinghua Yan [1], Yingying Xiu [1], Xinxian Xie [1] and Qi Wang [1,*]

[1] Yunnan Forestry Technological College, Kunming 650224, China; pangjing@yafg.ac.cn (J.P.); 2020020429@ynftc.edu.cn (C.S.); yqh@swfu.edu.cn (Q.Y.); ynftckjc@163.com (Y.X.); 18487252309@163.com (X.X.)
[2] Yunnan Key Laboratory of Biodiversity of Gaoligong Mountain, Kunming 650201, China; mengguangtao@yafg.ac.cn
[3] Yunnan Academy of Forestry and Grassland, Kunming 650201, China
* Correspondence: hena@yafg.ac.cn (N.H.); wangqi3858@126.com (Q.W.)

Abstract

In the context of global climate change, clarifying the effects of climatic factors on the potential distribution of forage grass species is critical for grassland development and ecological management. In this study, *Phleum pratense* was selected as the focal species, and an ensemble species distribution modeling framework was developed using the Biomod2 platform. After excluding highly correlated environmental variables, 17 ecologically meaningful predictors were retained to project the potential habitat suitability patterns of *P. pratense* and their future dynamics. The results indicate that the ensemble model achieved high predictive accuracy. Annual mean UV-B radiation, mean temperature of the driest quarter, and precipitation of the coldest quarter were identified as the primary climatic factors shaping the potential distribution of *P. pratense*. Under current climatic conditions, highly suitable habitats occupy a relatively limited and fragmented area, whereas low- and moderately suitable habitats predominate. Under future climate scenarios, increasing emission levels are associated with an overall contraction of moderately and highly suitable areas, accompanied by a continuous expansion of unsuitable habitats. In addition, the centroid of highly suitable habitats is projected to shift northwestward. These findings suggest that climate change may substantially alter the potential suitable range of *P. pratense* by modifying key climatic gradients and stress-period conditions. Overall, this study provides a scientific basis for the utilization of *P. pratense* germplasm resources and the sustainable development of plateau grassland systems.

Keywords: potential habitat suitability; species distribution models; climatic factors; stress-period constraints; grassland ecology

Check for updates

Academic Editor: Claudia D. Nicolae

Received: 27 January 2026
Revised: 7 February 2026
Accepted: 9 February 2026
Published: 28 February 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

1. Introduction

The establishment and spatial distribution of species populations are shaped by a wide range of environmental factors, including host plant availability, interspecific competition, and geographic conditions. From an ecological perspective, these drivers can be broadly categorized into biotic factors (e.g., species interactions, resource availability) and abiotic factors (e.g., climate, topography, and soil conditions), both of which jointly regulate species occurrence and population persistence [1,2]. However, climate has long been recognized as the primary determinant governing the successful introduction, establishment, and

persistence of newly introduced species [3,4]. Rising global temperatures not only influence species distributions and seasonal activity patterns but may also profoundly alter geographic ranges, potentially exacerbating outbreaks of harmful organisms or driving previously rare species toward extinction [5,6].

Species responses to climate change are not uniform but depend strongly on their ecological niche breadth [7]. Species with narrow ecological niches are particularly vulnerable, as continued contraction of their specialized habitats poses a direct threat to their long-term persistence. Such habitat specialists often exhibit limited physiological tolerance ranges and reduced adaptive capacity, making them highly sensitive to climatic fluctuations [8]. In contrast, other species may experience an expansion of suitable habitats in response to climate change, leading to a corresponding broadening of their geographic ranges. Generalist species, characterized by broader environmental tolerances, may thus benefit from changing climatic conditions, whereas specialist species are more likely to experience range contraction. These contrasting responses are consistent with fundamental ecological niche theory, which emphasizes the role of environmental constraints in shaping species' realized and potential distributions [9].

Consequently, the application of species distribution models to predict both realized and potential distributions has become a highly active and influential research area in regional ecology and biogeography. Currently, the most widely used models for delineating species distribution ranges include Bioclim (the bioclimatic analysis and prediction system), Ecological Niche Factor Analysis (ENFA), and the Maximum Entropy model (MaxEnt), among others [10–12]. Among these approaches, Biomod2 is an ensemble species distribution modeling platform that integrates multiple algorithms. By combining known species occurrence records with associated environmental variables, Biomod2 synthesizes predictions from different models to infer potential habitat suitability. This ensemble framework effectively reduces the uncertainty associated with individual models, thereby enhancing robustness and predictive accuracy. Moreover, its standardized workflow and broad applicability have made Biomod2 a widely adopted and reliable tool in species distribution research [13]. In recent years, Biomod2 has been extensively applied to predict suitable habitats for rare and endangered species and to simulate and assess the potential distribution ranges of invasive species [14]. Additionally, this approach has been widely employed to evaluate the potential spread risks of harmful organisms and to identify regions vulnerable to invasion under climate change scenarios [15].

Phleum pratense (commonly known as timothy grass) is a perennial, tuft-forming species belonging to the family Poaceae and the genus *Phleum*. It primarily occurs in grasslands and forest margins at elevations of approximately 1800 m and is naturally and widely distributed across temperate regions of Europe and Asia [16]. Ecologically, *P. pratense* can be regarded as a cool-season perennial grass with relatively specific climatic requirements, particularly with respect to temperature and moisture regimes. *P. pratense* is characterized by abundant foliage and a well-developed fibrous root system, which confer strong capacity for soil water purification and erosion control. Due to its high protein content and favorable fiber characteristics, it is among the most widely cultivated and utilized forage grasses worldwide. In addition, its relatively low potassium content helps regulate dietary cation–anion balance, making it an ideal roughage source for periparturient dairy cows. In recent years, Timothy grass has also gained prominence as a premium forage for companion animals, largely because its hay is rich in neutral detergent fiber and acid detergent lignin. These components provide herbivorous animals with adequate dietary fiber, promote digestive health, prevent gastrointestinal obstruction, mitigate excessive weight gain, and reduce the risk of urinary disorders [17,18].

North America serves not only as the global core production region for *P. pratense* but also as a pivotal hub in its international trade network. Canada, the leading producer, maintains an annual output of approximately 620,000 tons, more than 70% of which is exported—primarily to Japan, South Korea, and the United Arab Emirates—making it a major source of Timothy grass imports for China. In the United States, the Timothy grass industry pioneered a "pyramid market grading model" that maximizes profitability through precise segmentation of consumption scenarios. These international production and trade patterns further underscore the importance of understanding how climate change may affect the future availability and sustainability of P. pratense resources [19].

Climate change is the primary driver of gradual range shifts in *P. pratense*, with the potential to alter both the location and extent of its suitable habitats and thereby reshape its geographic distribution patterns [20,21]. This study focused on *P. pratense* and employed the Biomod2 ensemble modeling framework implemented in the R platform to predict dynamic changes in its potential distribution under current and future climate scenarios. Specifically, we aimed to (1) identify the key climatic factors limiting the current distribution of *P. pratense*, (2) assess changes in habitat suitability patterns under multiple Shared Socioeconomic Pathway (SSP) scenarios, and (3) quantify the spatial shifts of suitable habitat centroids in response to climate change. By addressing these objectives, this study seeks to improve our understanding of the climatic constraints governing P. pratense distribution and provide a scientific basis for germplasm conservation, breeding strategies, and sustainable management of high-altitude and temperate grassland ecosystems.

2. Materials and Methods

2.1. Species Occurrence Data Collection

Species occurrence records were compiled from geographic coordinates reported in the published literature and supplemented with distribution data obtained from the Global Biodiversity Information Facility (GBIF; https://www.gbif.org/, accessed on 18 April 2025) and the Chinese Virtual Herbarium (CVH; https://www.cvh.ac.cn/, accessed on 18 April 2025) for regions within China. To minimize the effects of duplicate records and spatial autocorrelation on model performance, occurrence points were spatially thinned using ENMTools version 1.4. A spatial resolution of 2.5 arc-minutes (approximately 4.5 km at the equator) was adopted to match the resolution of the climatic variable datasets, thereby ensuring consistency across spatial scales. Each grid cell was restricted to contain no more than one occurrence record. Following this filtering procedure, a total of 56 valid occurrence records of *P. pratense* were retained for subsequent ecological niche modeling analyses (Figure 1).

2.2. Environmental Variables

In this study, 19 bioclimatic variables were obtained from the WorldClim database (https://worldclim.org/, accessed on 20 April 2025). Future climate projections were also derived from WorldClim version 2.1, which provides downscaled climate data based on simulations from the Coupled Model Intercomparison Project Phase 6 (CMIP6). Three Shared Socioeconomic Pathway (SSP) scenarios—SSP1-2.6, SSP2-4.5, and SSP5-8.5—were selected to represent low-, intermediate-, and high-emission trajectories, respectively. To account for inter-model uncertainty, future climate variables were obtained from an ensemble of multiple Global Climate Models (GCMs) provided by WorldClim. Additional environmental datasets were sourced from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (https://www.resdc.cn/, accessed on 20 April 2025), the Harmonized World Soil Database (HWSD; https://gaez.fao.org/pages/hwsd, accessed on 20 April 2025), and the Center for International Earth Science Information Network

(CIESIN; https://ciesin.columbia.edu/, accessed on 20 April 2025). All datasets represented the most recent 2023 versions available from their respective sources. To reduce multicollinearity among environmental variables and mitigate potential model overfitting, the 19 bioclimatic variables were imported into ArcGIS 10.8, and values corresponding to the occurrence records of *P. pratense* were extracted. Pearson correlation analysis was subsequently performed, and only variables with correlation coefficients ($|r| < 0.8$) were retained for modeling. In addition, soil texture, soil organic carbon content, and topographic factors (e.g., elevation) were incorporated into the analysis to account for edaphic and physiographic influences on species distribution.

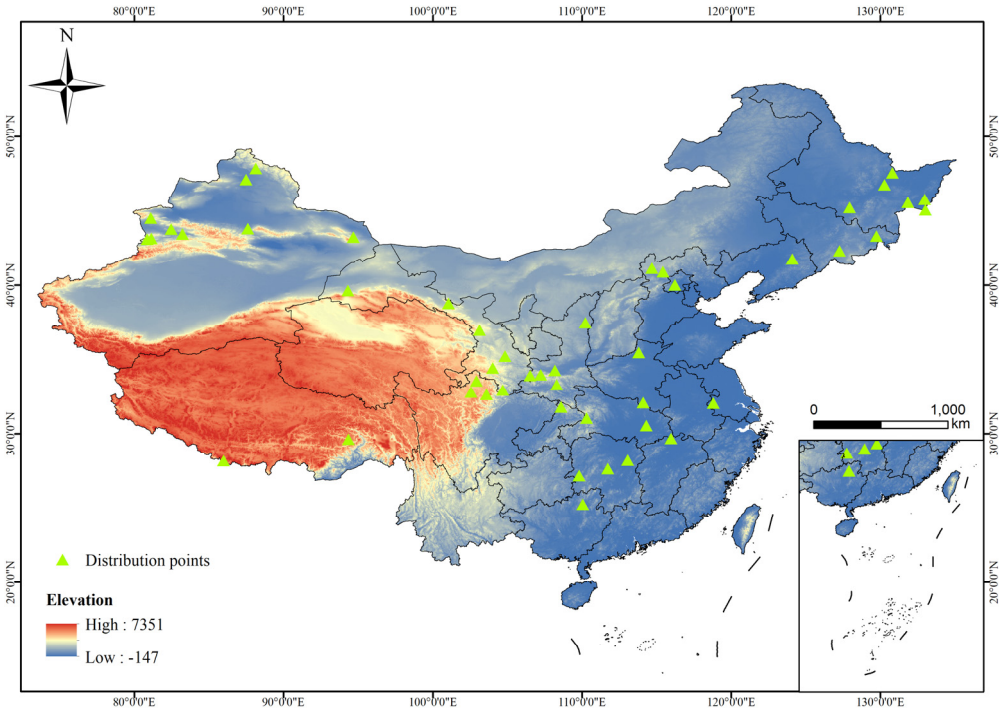


Figure 1. Valid occurrence points of *P. pratense* in China.

2.3. Model Construction

The R package Biomod2 integrates ten widely used species distribution models (SDMs), including Generalized Linear Models (GLM), Generalized Boosted Regression Models (GBM), Generalized Additive Models (GAM), Classification Tree Analysis (CTA), Artificial Neural Networks (ANN), Surface Range Envelope (SRE), Flexible Discriminant Analysis (FDA), Multivariate Adaptive Regression Splines (MARS), Random Forest (RF), and Maximum Entropy (MaxEnt). By employing an ensemble modeling approach, Biomod2 synthesizes predictions from multiple algorithms, thereby reducing systematic bias associated with individual models and enhancing overall predictive robustness and accuracy. During model development, 75% of the occurrence records were randomly assigned to the training dataset, while the remaining 25% were used as an independent test dataset for model validation. For each model, 1000 pseudo-absence points were randomly generated, and the modeling process was repeated ten times to reduce sampling-related uncertainty. Individual models were independently evaluated using performance metrics, including the Area Under the Receiver Operating Characteristic Curve (AUC) and the True Skill Statistic (TSS). The final ensemble model (EM) was subsequently generated by calculating a weighted average based on the predictive performance of each individual model, yielding a comprehensive prediction of the potential suitable habitats for *P. pratense*.

2.4. Model Evaluation and Habitat Suitability Classification

Variable importance was assessed using a permutation-based approach implemented in BIOMOD2, whereby the values of each predictor were randomly shuffled and the resulting change in model performance was used to quantify its relative contribution. The predictive performance of the ensemble model was evaluated using two metrics: the Kappa coefficient (KAPPA) and the True Skill Statistic (TSS). KAPPA ranges from −1 to 1, whereas TSS theoretically spans the same interval, with values closer to 1 indicating stronger model performance. According to commonly accepted classification criteria, both KAPPA and TSS values were interpreted as follows: 0–0.40, poor performance; 0.40–0.55, moderate performance; 0.55–0.70, good performance; 0.70–0.85, very good performance; and 0.85–1.00, excellent performance. Species suitability probabilities generated by the Biomod2 ensemble model were normalized to a 0–1 scale, representing the relative likelihood of species occurrence. Based on the TSS threshold, habitats were classified into four categories: unsuitable areas (probability < TSS threshold), low-suitability areas (TSS threshold $\leq$ probability < 0.33), moderate-suitability areas (0.33 $\leq$ probability < 0.66), and high-suitability areas (0.66 $\leq$ probability $\leq$ 1.00). Following model completion, Biomod2 outputs were imported into ArcGIS v10.8 for spatial analysis and raster overlay, enabling the quantification of area changes among different habitat suitability classes.

3. Results

3.1. Model Accuracy and Key Environmental Factors

To reduce the risk of overfitting associated with multicollinearity, highly correlated environmental variables with Pearson correlation coefficients exceeding 0.8 were excluded, thereby enhancing model robustness and predictive accuracy. Based on the ecological characteristics and habitat preferences of *P. pratense*, a total of 17 environmental variables were ultimately selected as the most informative predictors of species distribution (Table 1) and were subsequently used for model construction.

Table 1. Seventeen environmental variables selected for model construction.

Abbreviation	Description	Contribution
annual_mean_uv_b	The average annual UV-B radiation at the surface	47.20%
bio09	The average temperature during the driest quarter of the year	10.28%
bio19	Total precipitation during the coldest quarter	8.97%
bio08	The average temperature during the wettest quarter of the year	6.47%
bio16	Total precipitation during the wettest quarter	5.36%
bio07	The difference between the maximum temperature of the warmest month and the minimum temperature of the coldest month	5.36%
bio03	The ratio of mean diurnal temperature range to annual temperature range	5.14%
elev	Height above sea level	3.68%
gm_ve	Categorical variable representing vegetation classes	2.04%
bio02	The mean of monthly temperature ranges (max–min)	1.66%
slope	The degree of terrain inclination	1.49%
bio17	Total precipitation during the driest quarter	1.11%
bio15	Coefficient of variation of monthly precipitation	0.56%
gm_lc	Categorical land use/land cover classes such as forest	0.32%

Table 1. *Cont.*

Abbreviation	Description	Contribution
d1_ph_water	Distance from a location to the nearest permanent water body	0.28%
aspect	The compass direction that a slope faces	0.07%
d1_usda	Distance to the boundary between different USDA soil classification units	0.02%

All 12 individual models were successfully constructed, and their parameters were optimized using the biomod_tuning function in Biomod2. Model performance for each iteration was evaluated using the Receiver Operating Characteristic (ROC), Kappa, and True Skill Statistic (TSS) metrics, with the results indicating that parameter optimization substantially improved predictive accuracy. Among the models predicting the potential distribution of *P. pratense*, the Random Forest (RF) model exhibited the highest performance, achieving mean ROC and TSS values of 1.00 (Figure 2). In contrast, the Surface Range Envelope (SRE) and Artificial Neural Network (ANN) models showed slightly lower predictive accuracy, whereas the remaining nine models demonstrated moderate performance. For ensemble construction, only individual models with TSS values greater than 0.65 were retained. The resulting ensemble model achieved a TSS of 0.663 and an ROC value of 0.865, indicating high reliability and accuracy in predicting the potential distribution of *P. pratense*.

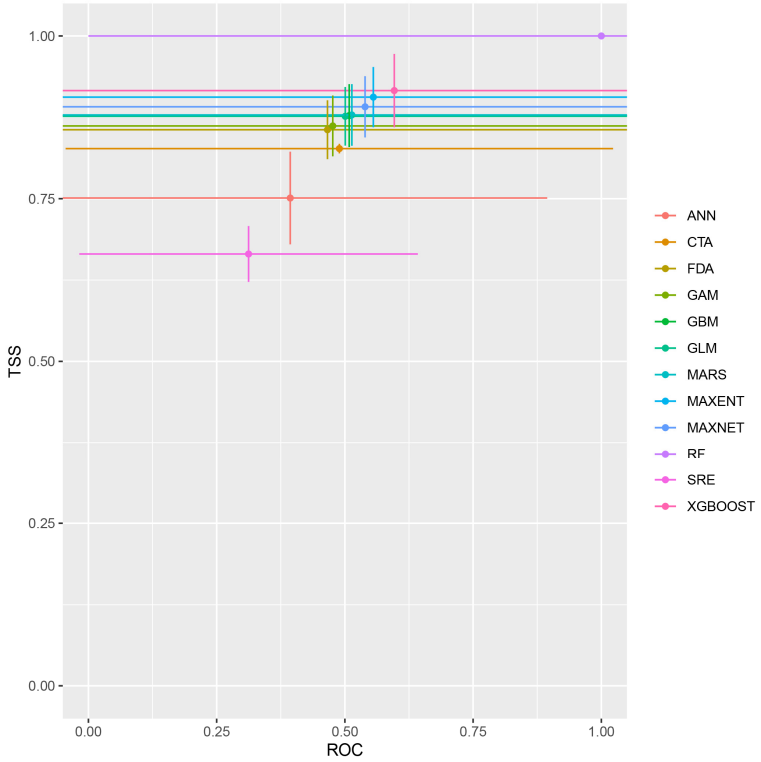


Figure 2. TSS and ROC values evaluating the performance of each individual model for *P. pratense*.

On the Biomod2 platform, the contributions of individual environmental variables to model predictions were quantified. The results indicated that the relative importance of each variable varied across individual models, with different factors exerting varying influences on predictive outcomes. In the ensemble model (EM) constructed from TSS-selected individual models, annual mean surface UV-B radiation made the largest contribution to the potential distribution of *P. pratense*. The six most influential bioclimatic variables in the ensemble model were ranked as follows: annual_mean_uv_b (mean annual surface

UV-B radiation, 47.20%), bio09 (mean temperature of the driest quarter, 10.28%), bio19 (total precipitation of the coldest quarter, 8.97%), bio08 (mean temperature of the wettest quarter, 6.47%), bio16 (total precipitation of the wettest quarter, 5.36%), and bio07 (temperature annual range, defined as the difference between the maximum temperature of the warmest month and the minimum temperature of the coldest month, 5.36%). Together, these variables accounted for a cumulative contribution of 83.64% (Figure 3).

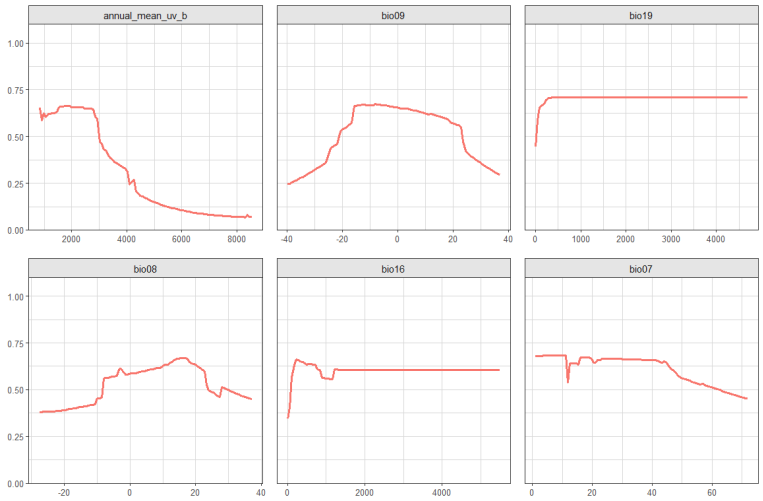


Figure 3. Response curves of the six bioclimatic variables with the highest contribution to the potential distribution of *P. pratense*.

3.2. Potential Distribution of *P. pratense* Under Current Climate Conditions

Under the current climatic scenario, highly suitable habitats for *P. pratense* are primarily concentrated in central Sichuan, southern Gansu, Shaanxi, Chongqing, Hubei, and Taiwan, with scattered occurrences in the northeastern part of the Xinjiang Uyghur Autonomous Region. Small, fragmented patches of highly suitable habitat are also present along the northeastern coastal provinces, including Heilongjiang, Jilin, and Liaoning (Figure 4). Overall, the total area of highly suitable habitat is relatively limited, covering approximately 27,000 km^2.

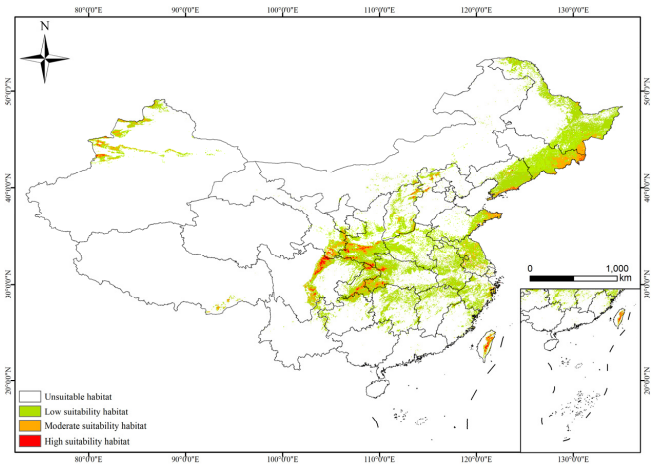


Figure 4. Global variation in the potential suitable habitats of *P. pratense* under current climatic conditions. Colors indicate suitability levels: red, highly suitable; orange, moderately suitable; green, low suitability; white, unsuitable.

Low- and moderately suitable habitats are predominantly distributed across China's second and third topographic steps, encompassing the eastern monsoon region and semi-humid to humid climatic zones. Spatially, these habitats extend broadly across Liaoning,

Jilin, Heilongjiang, Zhejiang, Fujian, Shandong, Jiangsu, Hebei, Shanxi, Anhui, Jiangxi, Henan, Hubei, Hunan, and Chongqing. The total areas of low- and moderately suitable habitats are approximately 1,127,600 km^2 and 196,800 km^2, respectively, both substantially larger than the area of highly suitable habitat. These patterns indicate that under the current conditions, *P. pratense* is predominantly distributed in low- to moderately suitable environments, whereas highly suitable habitats remain relatively restricted.

3.3. Changes in Habitat Area of P. pratense Under Future Climate Scenarios

This study evaluated changes in habitat suitability classes under current climatic conditions and future climate scenarios (SSP1-2.6, SSP2-4.5, and SSP5-8.5) (Figure 5). Across all scenarios and time periods, unsuitable habitats dominate the landscape and exhibit a clear expansion trend under future climatic conditions. The area of unsuitable habitat increases from approximately 7,956,300 km^2 at present, showing only minor fluctuations under SSP1-2.6 but expanding steadily under SSP2-4.5 and SSP5-8.5, ultimately reaching a maximum of 8,862,000 km^2 by 2090 under SSP5-8.5. In contrast, low-suitability habitats display a pronounced decline across all future scenarios, decreasing from 1,127,600 km^2 under current conditions to 374,300 km^2 by 2090 under SSP5-8.5. Moderately suitable habitats remain relatively limited in extent and exhibit scenario-dependent responses: they increase slightly under the low-emission SSP1-2.6 scenario but decline sharply under the high-emission SSP5-8.5 scenario, reaching only 60,600 km^2 by 2090. Highly suitable habitats consistently represent the smallest proportion and show a general contraction across all scenarios, shrinking from 27,000 km^2 at present to 10,700 km^2 by 2090 under SSP5-8.5 (Table 2). Overall, as emission intensity increases from low to high, suitable habitats—particularly moderately and highly suitable areas—continue to contract, while unsuitable habitats expand markedly. These trends indicate that future climate change may exert substantial negative impacts on the potential suitable range of *P. pratense*.

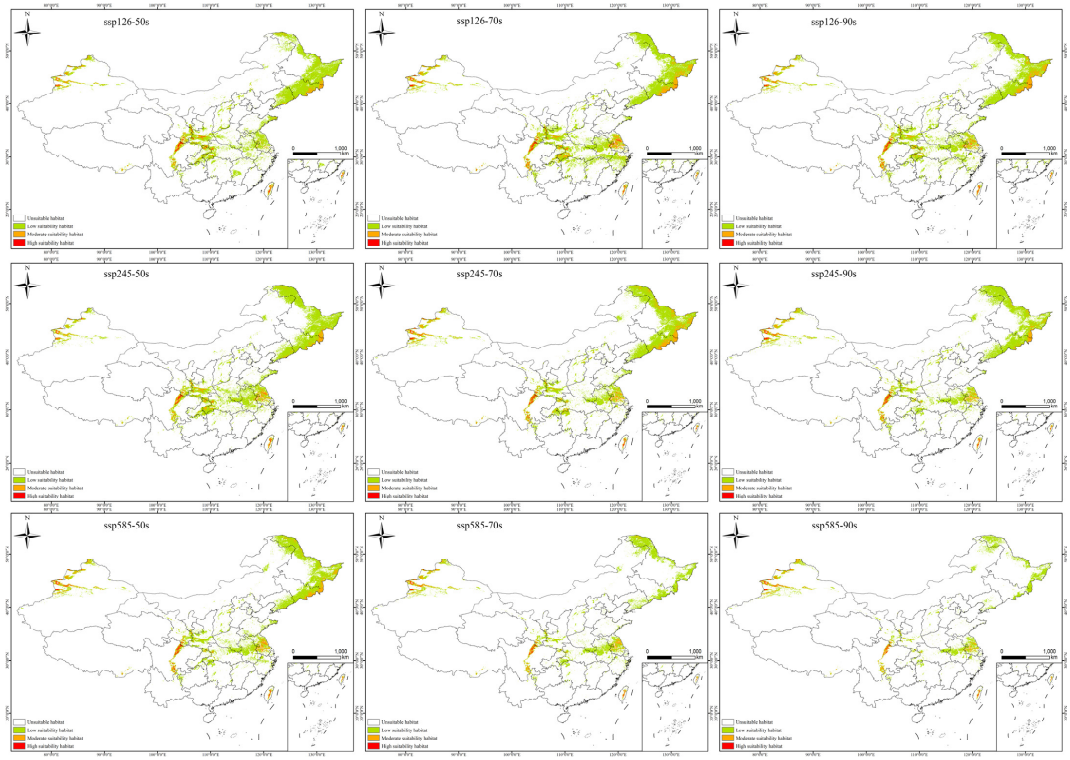


Figure 5. Global variation in the potential habitats of *P. pratense* under future climate scenarios. Colors indicate habitat suitability: red, highly suitable; orange, moderately suitable; green, low suitability; white, unsuitable.

Table 2. Habitat area of *P. pratense* under different climate scenarios (unit: 10,000 km^2).

		Unsuitable Habitat	Low Suitability Habitat	Moderate Suitability Habitat	High Suitability Habitat
current		795.6285	112.7587	19.6753	2.6962
ssp126	2050s	828.5868	88.7691	11.7674	1.6354
	2070s	817.7656	93.5955	17.1441	2.2535
	2090s	826.2622	87.2222	15.4063	1.8681
ssp2245	2050s	825.0382	92.0330	12.4913	1.1962
	2070s	832.1372	80.7344	16.2361	1.6510
	2090s	845.0156	73.9462	10.2135	1.5833
ssp585	2050s	839.5399	76.8490	12.6215	1.7483
	2070s	869.9514	52.7604	6.8507	1.1962
	2090s	886.1997	37.4288	6.0573	1.0729

3.4. Shifts in the Centroid of Highly Suitable Habitats Under Future Climate Conditions

Under current climatic conditions, the centroid of suitable habitats for *P. pratense* is located at 109.27° E, 33.39° N. Under the SSP1-2.6 scenario, the centroid exhibits an overall westward shift, although both migration direction and distance show noticeable temporal variability. By 2050, the centroid shifts markedly westward, followed by a reduced displacement with a slight northeastward adjustment in 2070, and then a renewed westward movement by 2090. Under the SSP2-4.5 scenario, the centroid consistently migrates toward the northwest, with the migration distance gradually decreasing over time—from 495.15 km in 2050 to 163.61 km by 2090—indicating a weakening and progressive stabilization of centroid movement. In contrast, under the high-emission SSP5-8.5 scenario, centroid shifts are the most pronounced and consistently oriented northwestward. The migration distance reaches 1040.16 km by 2050 and, although slightly reduced thereafter, remains strongly northwestward by 2090 (Table 3). Overall, as emission intensity increases from low to high, the migration distance of the suitable habitat centroid increases markedly, while the migration direction becomes increasingly stabilized toward the northwest (Figure 6). These spatial dynamics suggest that ongoing climate warming may drive the potential suitable range of *P. pratense* toward higher latitudes and more western regions.

Table 3. Coordinates, migration distances, and directions of the centroid of highly suitable habitats for *P. pratense*.

Period	x (Longitude, °E)	y (Latitude, °N)	Distance (km)	Direction
Current	109.2745	33.39122		
ssp126-50s	103.7417	34.10863	517.66	W
ssp126-70s	104.0508	34.32839	37.48	NE
ssp126-90s	102.6582	34.21046	128.64	W
Current	109.2745	33.39122		
ssp245-50s	104.0475	34.39553	495.15	NW
ssp245-70s	99.2619	35.61179	456.32	NW
ssp245-90s	97.48269	35.89519	163.61	NW
Current	109.2745	33.39122		
ssp585-50s	98.31312	35.90059	1040.16	NW
ssp585-70s	95.70679	36.93526	260.03	NW
ssp585-90s	93.46278	38.35572	252.93	NW

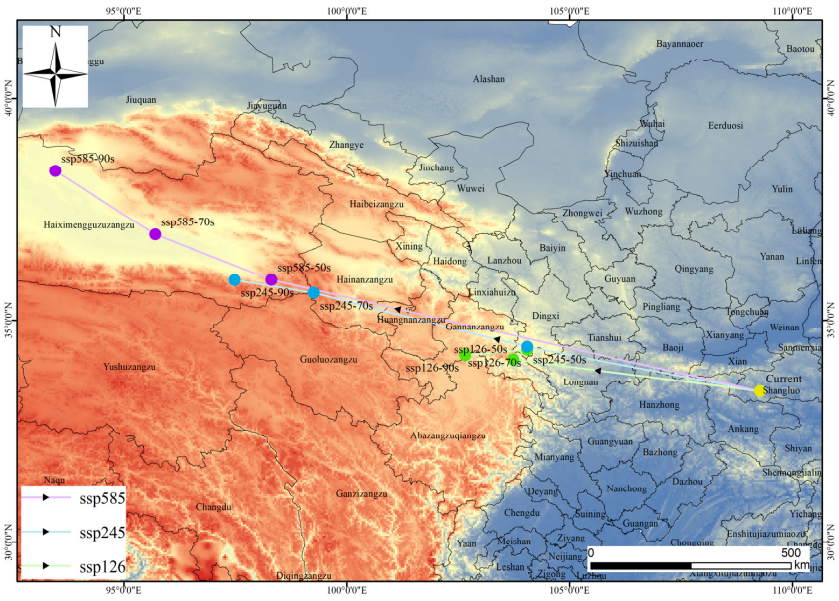


Figure 6. Shifts in the centroid of highly suitable habitats for *P. pratense* under future climate scenarios across different global regions.

4. Discussion

Climatic factors play a decisive role in shaping the distribution patterns of plant species. Under the context of global climate change, alterations in temperature and precipitation often exert direct effects on species' physiological processes and habitat suitability [22,23]. The ensemble modeling results based on the Biomod2 platform indicate that the potential distribution of *P. pratense* is primarily influenced by a combination of climatic factors, including annual_mean_uv_b, bio09, and bio19. Notably, the identification of UV-B radiation as a dominant limiting factor distinguishes this study from many previous species distribution modeling (SDM) analyses of forage grasses, which have primarily emphasized temperature and precipitation variables [24].

Among these, the annual mean UV-B radiation at the surface (annual_mean_uv_b) emerges as the most critical limiting factor, reflecting the species' adaptation to and constraints within high-altitude climatic conditions. From an ecological perspective, elevated UV-B radiation can affect plant growth by inducing DNA damage, altering photosystem II efficiency, and modifying leaf anatomical traits, thereby influencing photosynthetic performance and biomass accumulation [25]. Its contribution in the ensemble model is markedly higher than that of other variables, highlighting its key indicative value in predicting the distribution of *P. pratense* [26,27]. This variable likely serves as an integrated indicator of high-altitude or high-latitude climatic gradients rather than representing a single physiological stressor. In this sense, UV-B radiation may encapsulate the combined effects of elevation-related factors such as thinner atmospheric shielding, lower temperatures, and increased radiation intensity, which jointly shape the ecological niche of cold-season perennial grasses. Its spatial distribution closely aligns with the current highly suitable habitats of *P. pratense*, which are predominantly concentrated in the mountainous regions of southwestern China and certain high-latitude areas.

In addition to UV-B radiation, seasonal variations in temperature and precipitation also play significant roles in shaping the distribution of *P. pratense* [28,29]. The relatively high contribution of bio09 (mean temperature of the driest quarter) indicates that *P. pratense* is highly sensitive to temperature conditions during stress periods. During the driest quarter, elevated temperatures can exacerbate water stress by increasing evapotranspiration demand while soil moisture availability is limited, potentially leading to reduced

physiological activity or survival [30]. Whether temperatures in the driest season exceed its survival thresholds may directly determine the species' persistence and dispersal potential at a regional scale. Simultaneously, the importance of precipitation-related factors such as bio19 (total precipitation of the coldest quarter) further underscores that water availability across different seasons plays a regulatory role in defining the potential suitable range of *P. pratense* [31]. Cold-season precipitation, often occurring as snow in high-altitude or high-latitude regions, contributes to soil water recharge and may support early spring regrowth, thereby influencing population establishment and long-term persistence [32].

Under the current climatic conditions, the area of highly suitable habitats for *P. pratense* is relatively limited and exhibits a fragmented spatial pattern, primarily concentrated in the mountainous regions of southwestern China and certain high-latitude areas. In contrast, low- and moderately suitable habitats are broadly distributed across the eastern monsoon region and the semi-humid to humid climatic zones [33]. This distribution pattern, dominated by low- to moderately suitable habitats with relatively scarce highly suitable areas, reflects that *P. pratense* possesses a certain degree of environmental tolerance but exhibits stringent requirements for optimal habitat conditions [34]. On the one hand, the mountainous regions of southwestern China and high-latitude areas offer relatively moderate temperature and moisture conditions, which can partially satisfy *P. pratense* 's requirements for cool climates and seasonal precipitation. On the other hand, these regions are often characterized by high UV-B radiation and complex topography, resulting in highly suitable habitats that are fragmented and occur as discrete patches capable of sustaining long-term optimal conditions [35]. Importantly, habitat fragmentation should not be viewed solely as a spatial pattern, but also as an intrinsic biological risk, as it may restrict gene flow, reduce effective population sizes, and increase the vulnerability of local populations to stochastic disturbances [36]. Therefore, although *P. pratense* has a relatively wide potential distribution range in China, its highly suitable core habitats remain constrained by the combined effects of climatic and topographic conditions [37].

Under different future climate scenarios, the potential suitable habitats of *P. pratense* exhibit a clear trend of progressive contraction with increasing emission levels, particularly evident in the marked reduction in moderately and highly suitable areas, while unsuitable areas continue to expand. This pattern suggests that future climate warming may exert significant negative effects on the potential distribution of *P. pratense* by altering key climatic thresholds [38,39]. Under the high-emission scenario (SSP5-8.5), continuous temperature increases may push some of the currently low- to moderately suitable habitats beyond the optimal growth range of *P. pratense*. The combined effect of heightened thermal stress and the instability of precipitation patterns is likely to convert marginally suitable areas into unsuitable habitats first. In contrast, only certain high-latitude or high-altitude regions may maintain relatively favorable climatic conditions in the future, functioning as potential "climatic refugia" [40]. These refugial areas may play a critical role in buffering the impacts of climate change by providing stable microclimatic conditions that allow populations to persist despite broader regional warming trends [41].

Centroid analysis of suitable habitats further elucidates the spatial response of *P. pratense* to future climate change. As emission scenarios increase from low to high, the centroid of highly suitable areas exhibits a consistent northwestward shift, with migration distances notably greater under high-emission scenarios. This pattern suggests that climate warming may drive the potential distribution of *P. pratense* toward higher latitudes and elevations as a means of avoiding excessive thermal stress [42]. The relative consistency in migration direction reflects the dominant role of climatic factors in regulating species distribution at broad spatial scales.

From an applied perspective, the projected contraction and fragmentation of suitable habitats have important implications for in situ genetic resource conservation, breeding programs, and pasture management [43]. Fragmented high-suitability areas may harbor unique locally adapted genotypes, making them priority targets for conservation and germplasm collection. For breeding programs, identifying regions that overlap with future climatic refugia can guide the selection of source populations for developing cold- and stress-tolerant cultivars. In terms of pasture management, anticipating shifts in suitable areas can support proactive adjustments in cultivation planning and regional forage production strategies [44].

P. pratense is characterized by a wide distribution range and strong ecological adaptability, and its rich genetic variation provides an important material foundation for the breeding of superior cultivars and the development of grasses for ecological restoration [45,46]. The results of this study indicate that annual mean UV-B radiation, temperature, and precipitation are the key factors influencing the distribution of *P. pratense* in China. Under future climate change scenarios, its suitable range is likely to shift toward higher elevations and latitudes. Considering the current state of the *P. pratense* industry in China, high-altitude regions such as Min County in Gansu Province share high climatic similarity with potential future suitable areas, making them ideal candidate sites for the selection of cold- and stress-tolerant varieties and for regional trial cultivation. Moreover, by systematically collecting and evaluating germplasm resources of different ecological types, targeted breeding for cold- and drought-resilient traits can be pursued. Such efforts will not only enhance the cultivation stability of *P. pratense* in plateau and mountainous areas but also provide a scientific basis for the promotion of dual-purpose grasses for both ecological restoration and forage production.

Despite these insights, several limitations should be acknowledged. This study primarily relied on climatic and environmental variables and did not explicitly account for biotic interactions, dispersal constraints, or management practices that may influence species distributions at finer spatial scales [47]. In addition, uncertainties associated with future climate projections and SDM algorithms may affect the precision of predicted habitat shifts. Future research integrating population genetic data, field-based physiological experiments, and dynamic dispersal models would further improve our understanding of the adaptive capacity and long-term persistence of *P. pratense* under climate change.

5. Conclusions

This study systematically assessed the potential suitable distribution of *P. pratense* under current and future climatic conditions using the Biomod2 ensemble modeling approach. The results indicate that the species' potential distribution is jointly driven by multiple climatic factors, with annual mean UV-B radiation serving as a key indicative variable, reflecting its adaptation to and constraints within high-altitude environments. Additionally, the mean temperature of the driest quarter and seasonal precipitation patterns play critical roles in determining the species' survival and dispersal potential. Under current climate conditions, highly suitable habitats for *P. pratense* are limited in area and fragmented, with low- to moderately suitable environments predominating. Under future climate scenarios, as emission levels increase, suitable habitats—particularly moderately and highly suitable areas—are projected to shrink continuously, while unsuitable areas expand markedly. The centroid of highly suitable habitats shifts northwestward, suggesting that climate warming may drive the species' potential distribution toward higher latitudes and elevations. Overall, *P. pratense* exhibits high sensitivity to climatic gradients and critical stress-period conditions, and future climate change is likely to exert significant impacts on its potential distribution patterns. These findings provide a scientific basis for the introduction and

cultivation planning of *P. pratense*, germplasm selection, and the development of grasslands in plateau and mountainous regions.

Author Contributions: Conceptualization, J.P.; methodology, N.H.; software, J.P.; formal analysis, N.H. and J.P.; investigation, C.S. and Y.X.; data curation, X.X., G.M. and Q.Y.; writing—original draft preparation, J.P. and N.H.; writing—review and editing, N.H. and Q.W.; supervision, N.H. and Q.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Scientific Research Project of Yunnan Forestry Technological College (KY(ZD)202511), the Scientific and Technological Innovation Team Project of Yunnan Provincial Department of Education, the "Development and Application of Grass Seed Resources for Ecological Restoration", The Special Fund for Low-carbon Development Guidance in Yunnan Province, China, named "Research on the response of degraded grassland ecosystems in Yunnan to climate change", The 2025 Central Finance Forestry and Grassland Science and Technology Promotion and Demonstration Project (Yun [2025]TG11), and the Engineering Research Center of Yunnan Forestry Technological College (KY(ZX)202402).

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The data supporting the results are available in a public repository at: https://doi.org/10.6084/m9.figshare.31160266 (accessed on 28 January 2026.).

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Lewis, J.S.; Farnsworth, M.L.; Burdett, C.L.; Theobald, D.M.; Gray, M.; Miller, R.S. Biotic and abiotic factors predicting the global distribution and population density of an invasive large mammal. *Sci. Rep.* **2017**, *7*, 44152. [CrossRef] [PubMed]
2. Klanderud, K.; Vandvik, V.; Goldberg, D. The Importance of Biotic vs. Abiotic Drivers of Local Plant Community Composition Along Regional Bioclimatic Gradients. *PLoS ONE* **2015**, *10*, e0130205. [CrossRef] [PubMed]
3. Hulme, P.E. Climate change and biological invasions: Evidence, expectations, and response options. *Biol. Rev.* **2017**, *92*, 1297–1313. [CrossRef] [PubMed]
4. Du, Y.; Wang, X.; Ashraf, S.; Tu, W.; Xi, Y.; Cui, R.; Chen, S.; Yu, J.; Han, L.; Gu, S.; et al. Climate match is key to predict range expansion of the world's worst invasive terrestrial vertebrates. *Glob. Change Biol.* **2024**, *30*, e17137. [CrossRef]
5. Duffy, K.; Gouhier, T.C.; Ganguly, A.R. Climate-mediated shifts in temperature fluctuations promote extinction risk. *Nat. Clim. Change* **2022**, *12*, 1037–1044. [CrossRef]
6. Subedi, B.; Poudel, A.; Aryal, S. The impact of climate change on insect pest biology and ecology: Implications for pest management strategies, crop production, and food security. *J. Agric. Food Res.* **2023**, *14*, 100733. [CrossRef]
7. Thuiller, W.; Lavorel, S.; Araújo, M.B. Niche properties and geographical extent as predictors of species sensitivity to climate change. *Glob. Ecol. Biogeogr.* **2005**, *14*, 347–357. [CrossRef]
8. Huey, R.B.; Kearney, M.R.; Krockenberger, A.; Holtum, J.A.M.; Jess, M.; Williams, S.E. Predicting organismal vulnerability to climate warming: Roles of behaviour, physiology and adaptation. *Philos. Trans. R. Soc. B* **2012**, *367*, 1665–1679. [CrossRef]
9. Kambach, S.; Lenoir, J.; Decocq, G.; Welk, E.; Seidler, G.; Dullinger, S.; Gégout, J.-C.; Guisan, A.; Pauli, H.; Svenning, J.-C.; et al. Of niches and distributions: Range size increases with niche breadth both globally and regionally but regional estimates poorly relate to global estimates. *Ecography* **2019**, *42*, 467–477. [CrossRef]
10. Busby, J.R. BIOCLIM—A bioclimate analysis and prediction system. *Plant Prot. Q.* **1991**, *6*, 8–9.
11. Gui, T.; Lin, M.; Li, Z.; Peng, D.; Huang, Y.; Sun, W. Karyotyping and Distribution Patterns of Endemic Chinese Lilies: Insights Into Their Conservation Under Climate Change. *Ecol. Evol.* **2026**, *16*, e72824. [CrossRef]
12. Rebelo, H.; Jones, G. Ground validation of presence-only modelling with rare species: A case study on barbastelles *Barbastella barbastellus* (Chiroptera: Vespertilionidae). *J. Appl. Ecol.* **2010**, *47*, 410–420. [CrossRef]
13. Zhong, C.; Li, L.; Wang, Y.Z. Spatial and temporal distribution characteristics of *Paris polyphylla* var. *yunnanensis* and the prediction of steroidal saponins content. *Ind. Crops Prod.* **2025**, *227*, 120840. [CrossRef]
14. Urban, M.C. Climate change extinctions. *Science* **2024**, *386*, 1123–1128. [CrossRef] [PubMed]
15. Skendžić, S.; Zovko, M.; Živković, I.P.; Lešić, V.; Lemić, D. The Impact of Climate Change on Agricultural Insect Pests. *Insects* **2021**, *12*, 440. [CrossRef]

16. Moreno, S.; Bedada, G.; Rahimi, Y.; Ingvarsson, P.K.; Westerbergh, A.; Lundquist, P. Response to Waterlogging Stress in Wild and Domesticated Accessions of Timothy (*Phleum pratense*) and Its Relatives *P. alpinum* and *P. nodosum*. *Plants* **2023**, *12*, 4033. [CrossRef]
17. Houde, S.; Thivierge, M.; Fort, F.; Bélanger, G.; Chantigny, M.H.; Angers, D.A.; Vanasse, A. Root growth and turnover in perennial forages as affected by management systems and soil depth. *Plant Soil* **2020**, *451*, 371–387. [CrossRef]
18. Shackleton, J.; Boland, T.M.; Kennedy, J.; Grace, C.; Beaucarne, G.; Kirwan, S.F.; Schmidt, O.; Sheridan, H. Annual and seasonal dry matter production, botanical species composition, and nutritive value of multispecies, permanent pasture, and perennial ryegrass swards managed under grazing. *Grass Forage Sci.* **2024**, *79*, 630–650. [CrossRef]
19. Hellton, K.H.; Amdahl, H.; Thorarinsdottir, T.; Alsheikh, M.; Aamlid, T.; Jørgensen, M.; Dalmannsdottir, S.; Rognli, O.A. Yield predictions of timothy (*Phleum pratense* L.) in Norway under future climate scenarios. *Agric. Food Sci.* **2023**, *32*, 80–93. [CrossRef]
20. Rubenstein, M.A.; Weiskopf, S.R.; Bertrand, R.; Carter, S.L.; Comte, L.; Eaton, M.J.; Johnson, C.G.; Lenoir, J.; Lynch, A.J.; Miller, B.W.; et al. Climate change and the global redistribution of biodiversity: Substantial variation in empirical support for expected range shifts. *Environ. Evid.* **2023**, *12*, 7. [CrossRef]
21. Zhang, Z.; Xu, S.; Capinha, C.; Weterings, R.; Gao, T. Using species distribution model to predict the impact of climate change on the potential distribution of Japanese whiting *Sillago japonica*. *Ecol. Indic.* **2019**, *104*, 333–340. [CrossRef]
22. Huang, E.; Chen, Y.; Yu, S. Climate factors drive plant distributions at higher taxonomic scales and larger spatial scales. *Front. Ecol. Evol.* **2024**, *11*, 1233936. [CrossRef]
23. Zhao, Y.; Cao, H.; Xu, W.; Chen, G.; Lian, J.; Du, Y.; Ma, K. Contributions of precipitation and temperature to the large scale geographic distribution of fleshy-fruited plant species: Growth form matters. *Sci. Rep.* **2018**, *8*, 17017. [CrossRef] [PubMed]
24. Comont, D.; Winters, A.; Gomez, L.D.; McQueen-Mason, S.J.; Gwynn-Jones, D. Latitudinal variation in ambient UV-B radiation is an important determinant of *Lolium perenne* forage production, quality, and digestibility. *J. Exp. Bot.* **2013**, *64*, 2193–2204. [CrossRef]
25. Liaqat, W.; Altaf, M.T.; Barutçular, C.; Nawaz, H.; Ullah, I.; Basit, A.; Mohamed, H.I. Ultraviolet-B radiation in relation to agriculture in the context of climate change: A review. *Cereal Res. Commun.* **2024**, *52*, 1–24. [CrossRef]
26. Wang, X.; Zhao, G.; Chen, J.; Jing, F.; Li, L.; Wang, Y.; Ma, P.; Wu, Y.; Xu, S.; He, W. Adaptation of Plants to UV-B Radiation with Altitude in Tuha Basin: Synergistic Regulation of Epidermal Structure, Secondary Metabolites, and Organic Element Allocation. *Life* **2025**, *15*, 1375. [CrossRef]
27. Barnes, P.W.; Robson, T.M.; Zepp, R.G.; Bornman, J.F.; Jansen, M.A.K.; Ossola, R.; Wang, Q.W.; Robinson, S.A.; Foereid, B.; Klekociuk, A.R.; et al. Interactive effects of changes in UV radiation and climate on terrestrial ecosystems, biogeochemical cycles, and feedbacks to the climate system. *Photoch. Photobiol. Sci.* **2023**, *22*, 1049–1091. [CrossRef]
28. Alipour, S.; Behroozian, M. Potential impacts of climate change on the geographic distribution of Dionysia diapensiifolia Boiss., a rare and endemic species in Iran: Implications for conservation. *J. Nat. Conserv.* **2025**, *88*, 127050. [CrossRef]
29. Behroozian, M.; Amini, T.; Zare, H.; Ejtehadi, H. Assessing climate change impacts on the geographical distribution of Cupressus sempervirens in the Mediterranean region. *Sci. Rep.* **2025**, *15*, 40127. [CrossRef]
30. Qing, Y.; Wang, S.; Yang, Z.; Gentine, P.; Zhang, B.; Alexander, J. Accelerated soil drying linked to increasing evaporative demand in wet regions. *npj Clim. Atmos. Sci.* **2023**, *6*, 205. [CrossRef]
31. Zhou, Z.; Feng, H.; Ma, G.; Ru, J.; Wang, H.; Feng, J.; Wan, S. Seasonal and vertical patterns of water availability and variability determine plant reproductive phenology. *Ann. Bot.* **2025**, *135*, 211–222. [CrossRef] [PubMed]
32. Barnett, T.P.; Adam, J.C.; Lettenmaier, D.P. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* **2005**, *438*, 303–309. [CrossRef] [PubMed]
33. Lochan, R.; Sharma, D.K.; Kumar, A. Habitat suitability and projecting distribution shifts of Himalayan Monal (*Lophophorus impejanus*) habitats across changing landscapes of the Indian Himalayan region. *Sci. Rep.* **2025**, *15*, 25622. [CrossRef] [PubMed]
34. Tomar, S.; Thakur, S.; Kanwal, K.S.; Bhatt, I.D.; Puri, S. Population assessment and habitat suitability modelling of endangered medicinal plant, *Aconitum heterophyllum* Wall. ex Royle in the western Himalaya. *Sci. Rep.* **2025**, *15*, 33794. [CrossRef]
35. Wang, H.; Wonkka, C.L.; Treglia, M.L.; Grant, W.E.; Smeins, F.E.; Rogers, W.E. Species distribution modelling for conservation of an endangered endemic orchid. *Aob Plants* **2015**, *7*, plv039. [CrossRef]
36. González, A.V.; Gómez-Silva, V.; Ramírez, M.J.; Fontúrbel, F.E. Meta-analysis of the differential effects of habitat fragmentation and degradation on plant genetic diversity. *Conserv. Biol.* **2020**, *34*, 711–720. [CrossRef]
37. Caballero-Villalobos, L.; Fajardo-Gutiérrez, F.; Calbi, M.; Silva-Arias, G.A. Climate Change Can Drive a Significant Loss of Suitable Habitat for *Polylepis quadrijuga*, a Treeline Species in the Sky Islands of the Northern Andes. *Front. Ecol. Evol.* **2021**, *9*, 661550. [CrossRef]
38. Bhuyan, A.; Bawri, A.; Saikia, B.P.; Baidya, S.; Hazarika, S.; Thakur, B.; Chetry, V.; Deka, B.S.; Bharali, P.; Prakash, A.; et al. Predicting habitat suitability of *Illicium griffithii* under climate change scenarios using an ensemble modeling approach. *Sci. Rep.* **2025**, *15*, 9691. [CrossRef]

39. Cai, Z.; Li, F.; Bao, S.; Zhang, H.; Shi, J. Climate Change and Habitat Fragmentation: Implications for the Future Distribution and Assisted Migration of *Kobresia pygmaea*. *Plants* **2025**, *14*, 3585. [CrossRef]
40. Lee, J.; Lee, E.; Lee, J.; Seo, C. Mapping Endangered Plant Distributions, Species Richness, and Climate Refugia Under SSP Climate Scenarios in South Korea. *Plants* **2025**, *14*, 3735. [CrossRef]
41. Suggitt, A.J.; Wilson, R.J.; Isaac, N.J.B.; Beale, C.M.; Auffret, A.G.; August, T.; Bennie, J.J.; Crick, H.Q.P.; Duffield, S.; Fox, R.; et al. Extinction risk from climate change is reduced by microclimatic buffering. *Nat. Clim. Change* **2018**, *8*, 713–717. [CrossRef]
42. Chen, I.; Hill, J.K.; Ohlemüller, R.; Roy, D.B.; Thomas, C.D. Rapid Range Shifts of Species Associated with High Levels of Climate Warming. *Science* **2011**, *333*, 1024–1026. [CrossRef]
43. Christmas, M.J.; Breed, M.F.; Lowe, A.J. Constraints to and conservation implications for climate change adaptation in plants. *Conserv. Genet.* **2016**, *17*, 305–320. [CrossRef]
44. John, A.; Michalak, J.; Svancara, L.; Randels, C.; Lawler, J. Identifying climate-change refugia for species management and conservation in the Pacific Northwest. *Conserv. Sci. Pract.* **2025**, *8*, e70174. [CrossRef]
45. Salgotra, R.K.; Chauhan, B.S. Genetic Diversity, Conservation, and Utilization of Plant Genetic Resources. *Genes* **2023**, *14*, 174. [CrossRef]
46. Loera-Sánchez, M.; Studer, B.; Kölliker, R. DNA-Based Assessment of Genetic Diversity in Grassland Plant Species: Challenges, Approaches, and Applications. *Agronomy* **2019**, *9*, 881. [CrossRef]
47. Wisz, M.S.; Pottier, J.; Kissling, W.D.; Pellissier, L.; Lenoir, J.; Damgaard, C.F.; Dormann, C.F.; Forchhammer, M.C.; Grytnes, J.; Guisan, A.; et al. The role of biotic interactions in shaping distributions and realised assemblages of species: Implications for species distribution modelling. *Biol. Rev.* **2013**, *88*, 15–30. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.