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ADAPTIVE DISTRIBUTION OF A HIGH-ALTITUDE ENDEMIC PLANT WITH SIGNIFICANT MEDICINAL POTENTIAL UNDER CLIMATE CHANGE

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Abstract

Clematis tenuifolia Royle is an important medicinal plant of the Ranunculaceae family with great relevance in Tibetan medicine. The research used an adjusted MaxEnt model and ArcGIS software, which incorporates multi-source environmental information such as climate, soil and human activity, to predict the existing and future potential distribution of the appropriate habitat of *Clematis tenuifolia* across four CMIP6 climate scenarios (SSP1-2.6 to SSP5-8.5). This study identified the key environmental influences and analyzed the spatial variation properties. The results show that: (1) Important ecological variables affecting distribution include the ratio of the diurnal and annual temperature range (bio3), mean temperature of the wettest season (bio8), and mean temperature of the driest season (bio9); (2) Based on the existing situation, the total area of the suitable habitat is about 103.97×10^4 km^2, and most of it is located in southern Tibet and southwestern Sichuan; (3) In future climate scenario, the area of suitability shows a strong tendency to shrink. The high-suitability region withdraws to localized regions in southeastern parts of Tibet, whereas the center of gravity of the suitable region, as a whole, moves southeast towards the Bomi–Medog area of Nyingchi City. These results suggest that the seasonal temperature change is the main factor that influences the distribution of *Clematis tenuifolia*, and its suitable habitat will be reduced in size and shifted to small-scale locations in southeastern Tibet. Consequently, future efforts should prioritise the protection of potential "climatic refuges" in the Bomi–Medog region of southeastern Tibet. Concurrently, dynamic monitoring and sustainable utilisation of existing high-suitability habitats in southern Tibet and southwestern Sichuan must be emphasised to mitigate the distribution contraction risks posed by climate change to this species.

Key words: *Clematis tenuifolia* Royle; MaxEnt model; Habitat prediction; ENMeval

Introduction

Clematis is a widely distributed and morphologically diverse genus within the Ranunculaceae family, comprising over 300 species. It is primarily found in temperate and subtropical regions globally, with particular species richness in the Northern Hemisphere. China serves as one of its centres of distribution, hosting approximately 108 species (as recorded in Flora of China) (Anon., 1990). Modern medical research has revealed the medicinal value of numerous species within the Clematis genus. China's documented history of utilising Clematis plants for medicinal purposes dates back to the Tang Dynasty (Hao *et al*., 2024) For instance, the Newly Revised Materia Medica records that *Clematis chinensis* (Weilingxian) possesses efficacy in treating various wind disorders, promoting the smooth functioning of the five viscera, eliminating abdominal cold stagnation, and, when taken long-term, imparting a sense of lightness to the body (Jing, 2004). As traditional Chinese medicine continues to develop, the study on the medicinal value of Clematis species has become more intense in recent years. To give an example, the pharmacological effect of *Clematis chinensis* and *C. chinensis* var. *villosa* are found to be analogous with that of *Clematis chinensis*, which are found to have a great therapeutic value (Caixia *et al*., 2006; Tang *et al*., 2021).

Clematis tenuifolia as an endemic species of this genus to the Qinghai-Tibet Plateau and surrounding high-altitude regions, possesses a long history of application within Tibetan pharmacology. The Tibetan medical classic, The Crystal Essence of Materia Medica, refers to it as "Yuwa", recording its medicinal properties as "pungent and bitter in taste, warm in nature" (Rodarthean, 2004). It is commonly employed for rheumatic arthralgia and stiffness of tendons and bones. However, compared to other well-studied species within the genus, modern scientific understanding of *C. tenuifolia* remains relatively limited. In particular, systematic assessments of its potential distribution range, ecological adaptability, and response to future climate change are lacking. This deficiency to some extent constrains the scientific conservation and sustainable utilisation of this species' resources.

MaxEnt (Maximum Entropy Model), as a species distribution model grounded in niche theory, analyses known distribution point data and environmental variable data. Based on the principle of maximum entropy, it produces a probability distribution with the highest level of uncertainty (i.e., the most homogeneous distribution) subject to the constraints known and therefore can be used to infer the possible distribution of species at different environmental conditions (Ma *et al*., 2023). This model is not based on a full background information, has great flexibility in using small sample sizes and can visually depict the relationship between species and environmental parameters. It has therefore been widely used in predicting the species distribution (Gao *et al*., 2022; Ngarega *et al*., 2024).

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Nevertheless, conventional MaxEnt models have problems in practice, including overly subjective parameter settings and sensitivity to overfitting, which can result in skewed predictions (Hazarika *et al.*, 2025). In order to solve this problem, this research will use the ENMeval package to optimize the MaxEnt model (Yang *et al.*, 2025). The ENMeval uses information-theoretic measures (AICc and BIC) to systematically test model performance with cross-validation given different combinations of parameters. Optimal regularisation parameters and feature set are automatically selected, which helps in reducing overfitting risks and improving the prediction accuracy and robustness substantially (Novoseltseva, 2024; Waheed *et al.*, 2025). This optimised MaxEnt model has demonstrated considerable advantages across numerous fields, including biodiversity conservation and the prediction and protection of distribution areas for rare and endangered species (Shi *et al.*, 2024). This study employs the ENMeval-optimised MaxEnt model to conduct scientific predictions of the current and future potential suitable habitats for *C. tenuifolia*. This provides crucial foundational data support for medicinal research on this species and aids in the rational planning of germplasm resource conservation and utilisation strategies.

Materials and Methods

Acquisition and screening of distribution points: The acquisition of sample points for this study was primarily achieved through field survey records and queries of the Global Biodiversity Information Facility (GBIF; https://www.gbif.org/), alongside academic platforms such as the China Digital Specimen Museum (https://www.cvh.ac.cn/index.php) and CNKI. This process yielded a total of 123 sample point records for *Clematis tenuifolia*. To prevent overfitting, collected points were imported into ENMtools for de-fitting (Hou *et al.*, 2023). Subsequently, using ArcGIS 10.8 software, a 5 km × 5 km spatial grid network was constructed via buffer analysis. During grid processing, multiple overlapping sampling points were reduced to a single representative point, and those with anomalous geographical coordinate data were excluded (Paul & Samant, 2024). Following this screening process, 46 valid sampling points for *Clematis tenuifolia* were ultimately obtained is shown in Fig. 1.

Filtering of environment variables: This study incorporated a total of 59 environmental variables, encompassing 19 bioclimatic variables, elevation, slope gradient and aspect, soil environmental variables, and human activity indicators. Altitude and slope aspect data, along with climatic variables, were sourced from the WorldClim website (https://www.worldclim.org/). Soil environmental variables were obtained from the National Soil Environment Information Platform (http://soilcredit.mee.gov.cn). Information on human activities was mainly derived using the WorldClim 2.0 database. The reduction of the influence of multicollinearity between environmental variables on model accuracy and predictive capability (Warren *et al.*, 2010), environmental variables underwent rigorous scientific screening. Initially, Pearson correlation analysis was performed using R software is shown in Fig. 2, excluding factors with absolute correlation coefficients exceeding 0.8. Further collinearity factors were removed via variance inflation factor (VIF) testing (threshold set at VIF > 10), yielding 10 environmental factors. Subsequently, these 10 environmental factors were input into the Maxent model. Combined with species distribution point data, the percentage contribution and displacement importance of each factor were calculated based on the Maxent model. Environmental factors with a contribution rate >1% were selected, ultimately identifying five primary environmental factors is shown in Table 1:Diurnal temperature range relative to annual temperature range (bio3), mean temperature of the wettest season (bio8), mean temperature of the driest season (bio9), basic saturation of topsoil (t_bs), and human footprint (hfp) (Phillips *et al.*, 2006; Phillips *et al.*, 2017).

To investigate the impact of future climate change on the suitable habitat of *C. tenuifolia*. in Tibet, CMIP6 and CMCC-ESM2 climate model data were employed. The present period spaning 1970–2000, with analyses conducted for two future timeframes: 2041–2060 and 2061–2080. The models considered four representative socio-economic development scenarios: Sustainable Development Pathway (SSP1-2.6), Intermediate Development Pathway (SSP2-4.5), Regional Competition Pathway (SSP3-7.0), and High Emission Pathway (SSP5-8.5) (Zheng *et al.*, 1999; Chen *et al.*, 2022). The aforementioned ecological and environmental factor data were imported into the geographic information system ArcGIS 10.8 for preprocessing, ensuring consistency in the coordinates, pixel size, and extent of the environmental data. Subsequently, the SDMtoolbox plugin was employed to convert the layers into the ASC format compatible with MaxEnt software, with the output saved in ASCII format for future use (Zhang *et al.*, 2019).

Optimization and Analysis of the MaxEnt Model: MaxEnt default parameters (such as regularization multiplier = 1 and feature combination "LQHPT") readily lead to model overfitting on training data, diminishing predictive capability in new environments. Moreover, these default parameters are not optimized for specific species or environmental datasets, potentially failing to capture genuine niche relationships (Hongpei *et al.*, 2025). Thus, application of ENMeval via parameter optimization, spatial validation and variable screening greatly improves the predictive accuracy, interpretability as well as the academic rigor of MaxEnt models (Booth *et al.*, 2014). The regularization multiplier (RM) and feature combination (FC) are important factors that affect the complexity of MaxEnt models (Shi *et al.*, 2023). To regularize this research the regularization multiplier was fixed at intervals of 0.5, with a minimum of 0.5 and a maximum of 4, and four feature combinations were used namely, L, LQ, LQH and LQP. The optimization of MaxEnt over these 32 combinations of parameters demonstrated that lower DeltaAICc values are indicative of better predictive performance. Results indicated that DeltaAICc value equaled zero which is the best parameters when the regularization multiplier was 3 and the feature combination was LQ (Lou *et al.*, 2022).

Results

Construction and accuracy evaluation of the MaxEnt model: The five selected environmental factors and 46 distribution sample points were formatted as required and imported into MaxEnt 3.4.4 software. When running the MaxEnt model, optimized parameters were selected for feature combinations and regularization. Twenty-five percent of sample point data were randomly selected as the test set, with the remaining 75% forming the training set (Low *et al.*, 2021). Employ the "Subsample" iterative method for 10 iterations to fit the model, with a maximum iteration count of 5000. Enable Jackknife validation and response curve plots, outputting results in Logistic format while retaining default settings for other parameters. Model accuracy was assessed using the miss rate and Area Under the Curve (AUC) value of the ROC curve (Guo *et al.*, 2023). The AUC value ranges between 0 and 1, with values closer to 1 indicating optimal predictive performance. Generally, an AUC value below 0.6 signifies poor prediction, 0.6–0.7 denotes average results, 0.7–0.8 indicates suboptimal performance, 0.8–0.9 suggests good prediction, and an AUC value above 0.9 indicates excellent prediction (Ab Lah *et al.*, 2021). Under the current environmental factors, the miss rate and ROC curve for this study are shown in Fig. 3. The AUC value of 0.989 indicates a high degree of fit, demonstrating excellent prediction results and confirming the model's robust performance.

Dominant environmental factors influencing the distribution of *Clematis tenuifolia*: As illustrated in Fig. 4, the five key variables influencing the potential distribution of *C. tenuifolia* are, in order of importance: the ratio of diurnal to annual temperature variation, the mean temperature of the wettest season, the mean temperature of the driest season, the basic saturation of the topsoil, and the impact of human activity. Among environmental factors, the combined contribution rate of the ratio of diurnal to annual temperature variation, the mean temperature of the wettest season, and the mean temperature of the driest season reached 84.4%. Consequently, these three bioclimatic variables are pivotal in predicting the distribution of suitable habitats for *C. tenuifolia*. The findings indicate is shown in Fig. 5 that the probability of *C. tenuifolia* occurrence gradually increases with rising ratios of diurnal to annual temperature variation; whilst the probability of *C. tenuifolia*. occurrence also increases with rising average temperatures during the wettest season. However, when the average temperature of the wettest season reaches approximately 7°C, further increases in temperature lead to a gradual decrease in the probability of occurrence. Similarly, the probability of occurrence peaks when the average temperature of the driest season reaches −1°C, but shows a declining trend with further temperature increases.

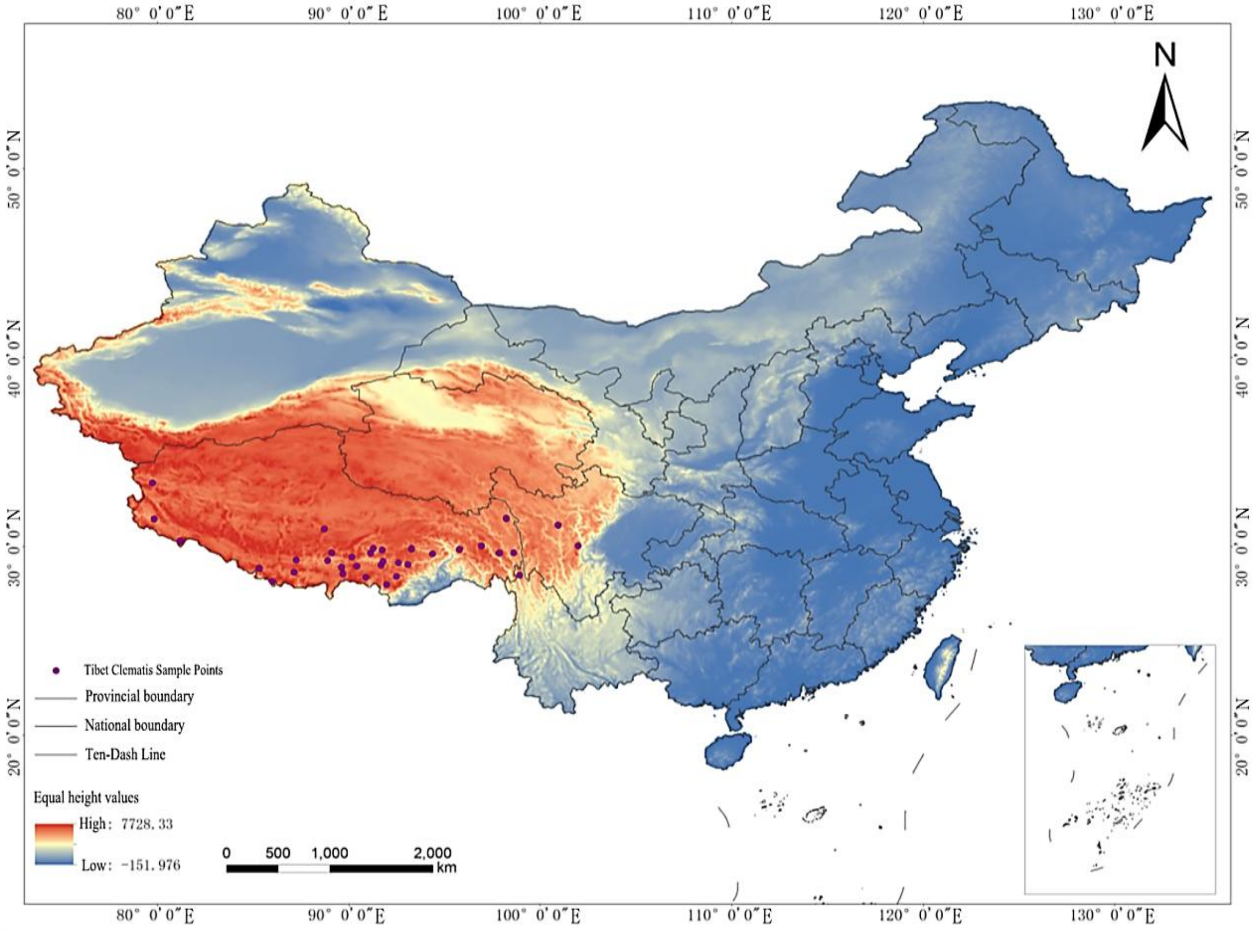

Fig. 1. Current distribution of validated *Clematis tenuifolia* records across China. The map was generated using ArcMap 10.8 (ESRI, Redlands, CA, USA). Administrative boundaries were sourced from the National Geomatics Center of China (http://www.ngcc.cn) and projected in the WGS84 coordinate system.

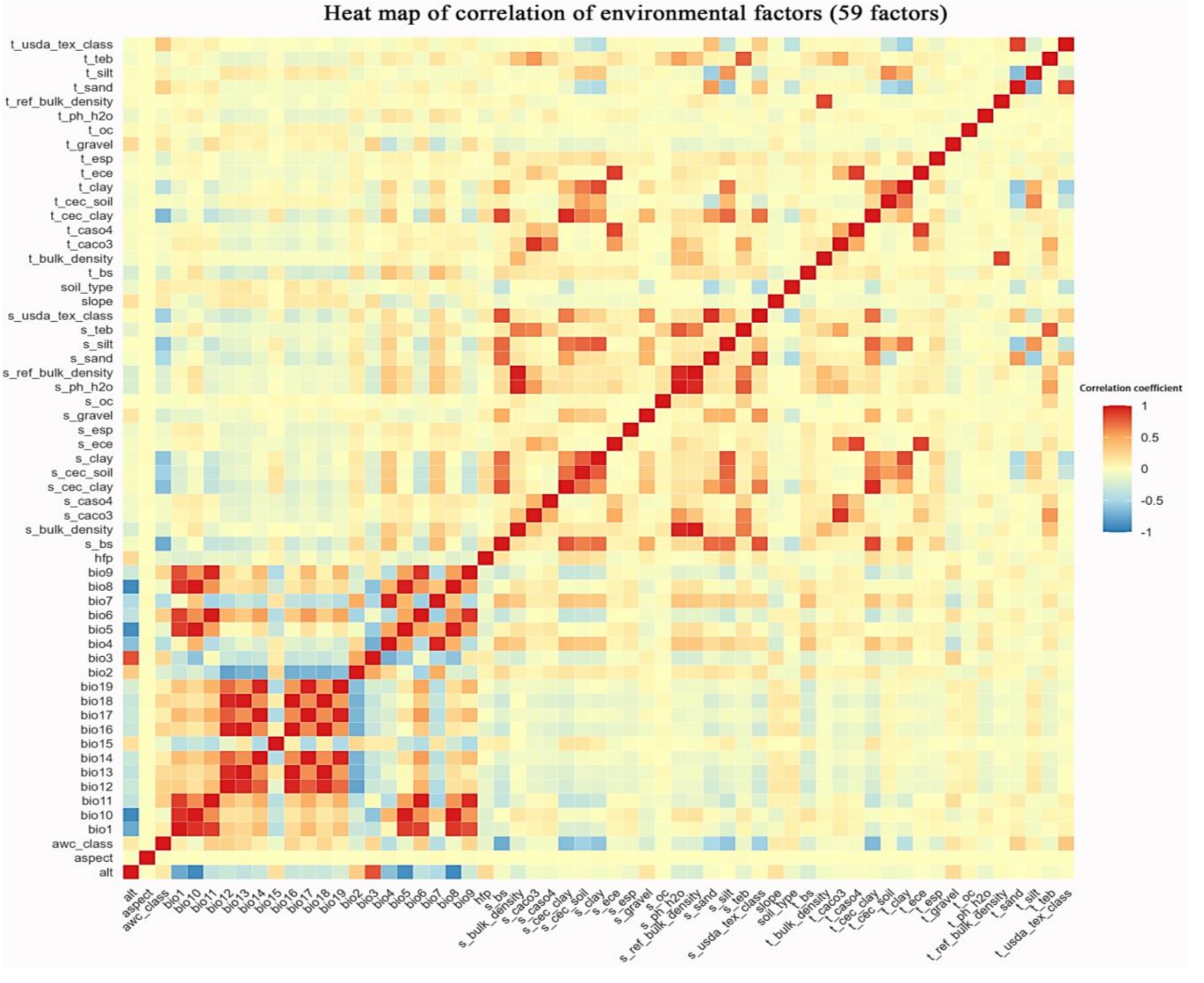

Fig. 2. Correlation analysis of 59 environmental factors.

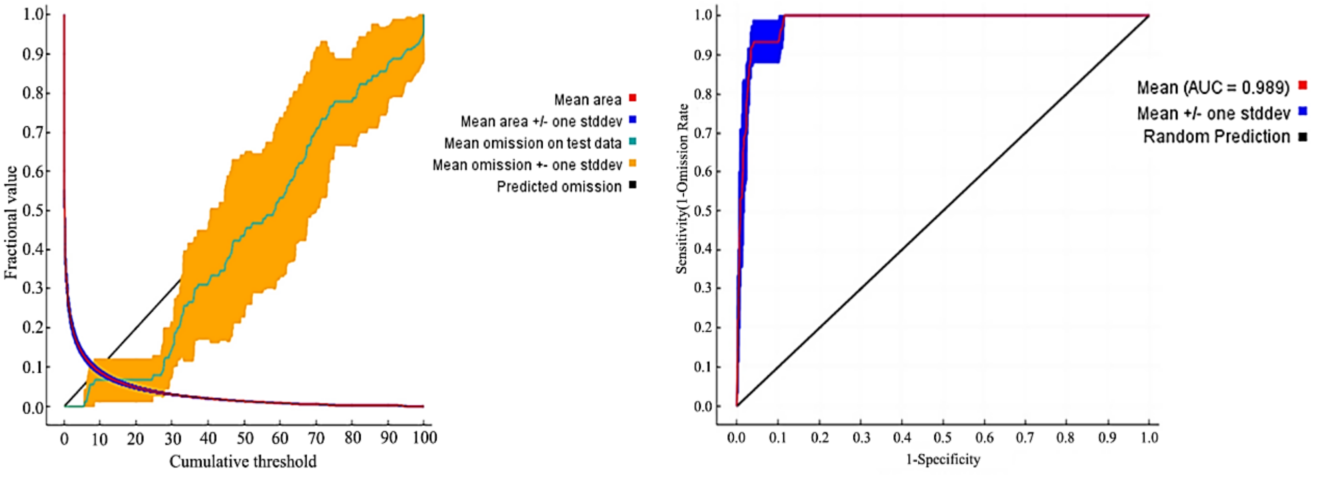

Fig. 3 Omission rate and ROC curve for *Clematis tenuifolia*.

Table 1. Contribution and importance of environmental variables.

Code	Variable	Unit	Contribution (%)	Permutation importance (%)
bio3	Isothermality (diurnal/annual temperature range ratio)	-	53.4	29.6
bio8	Mean temperature of wettest quarter	°C	15.6	44.6
bio9	Mean temperature of driest quarter	°C	15.4	20.2
t_bs	Base saturation (topsoil 0-30 cm)	%	12.1	3.6
hfp	Human Footprint Index	%	3.5	2.0

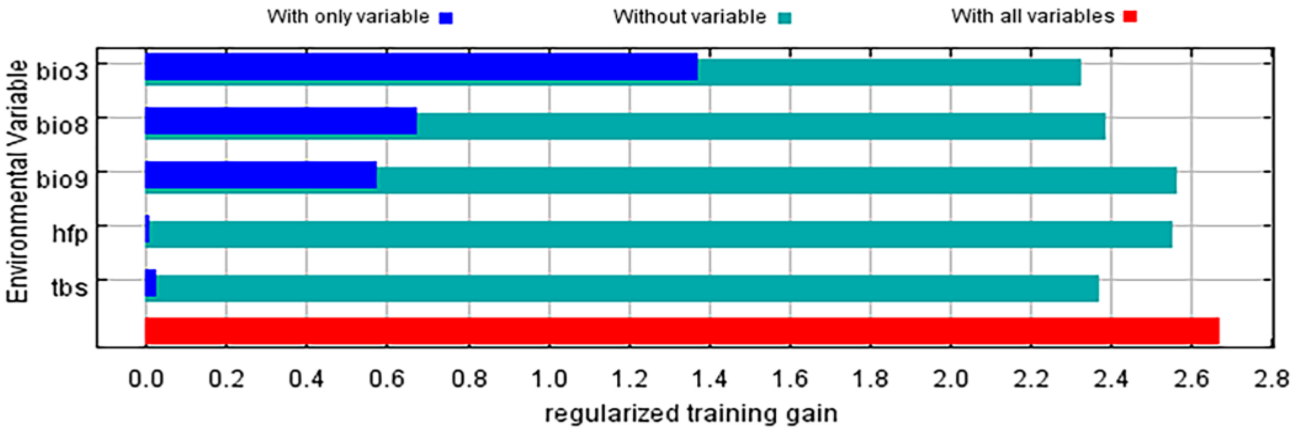

Fig. 4. Jackknife test of environmental variable importance for the potential distribution model of *C. tenuifolia*. bio3: ratio of diurnal to annual temperature difference; bio8: mean temperature of the wettest quarter; bio9: mean temperature of the driest quarter; t_bs: base saturation of topsoil; hfp: human footprint index.

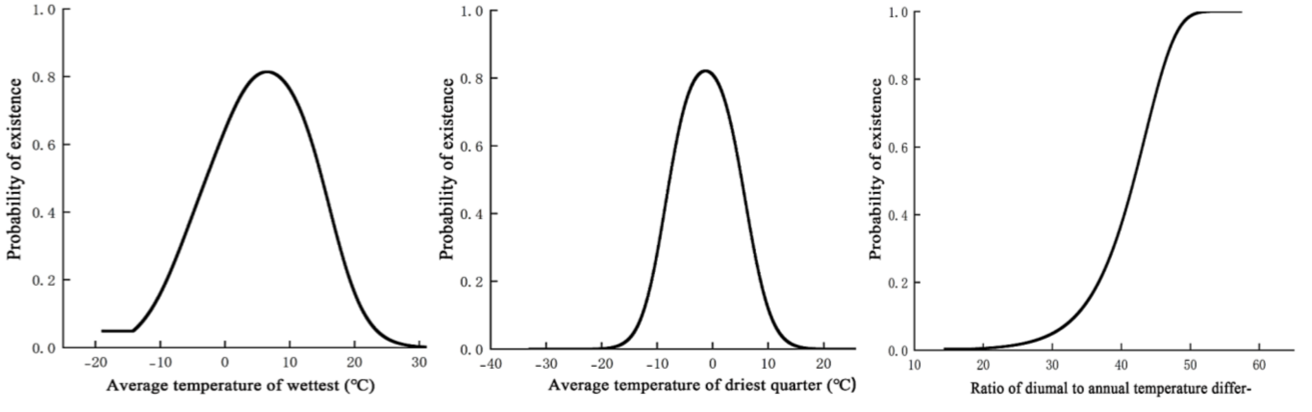

Fig. 5. Response curves of important environmental factors affecting the potential distribution of *Clematis tenuifolia*.

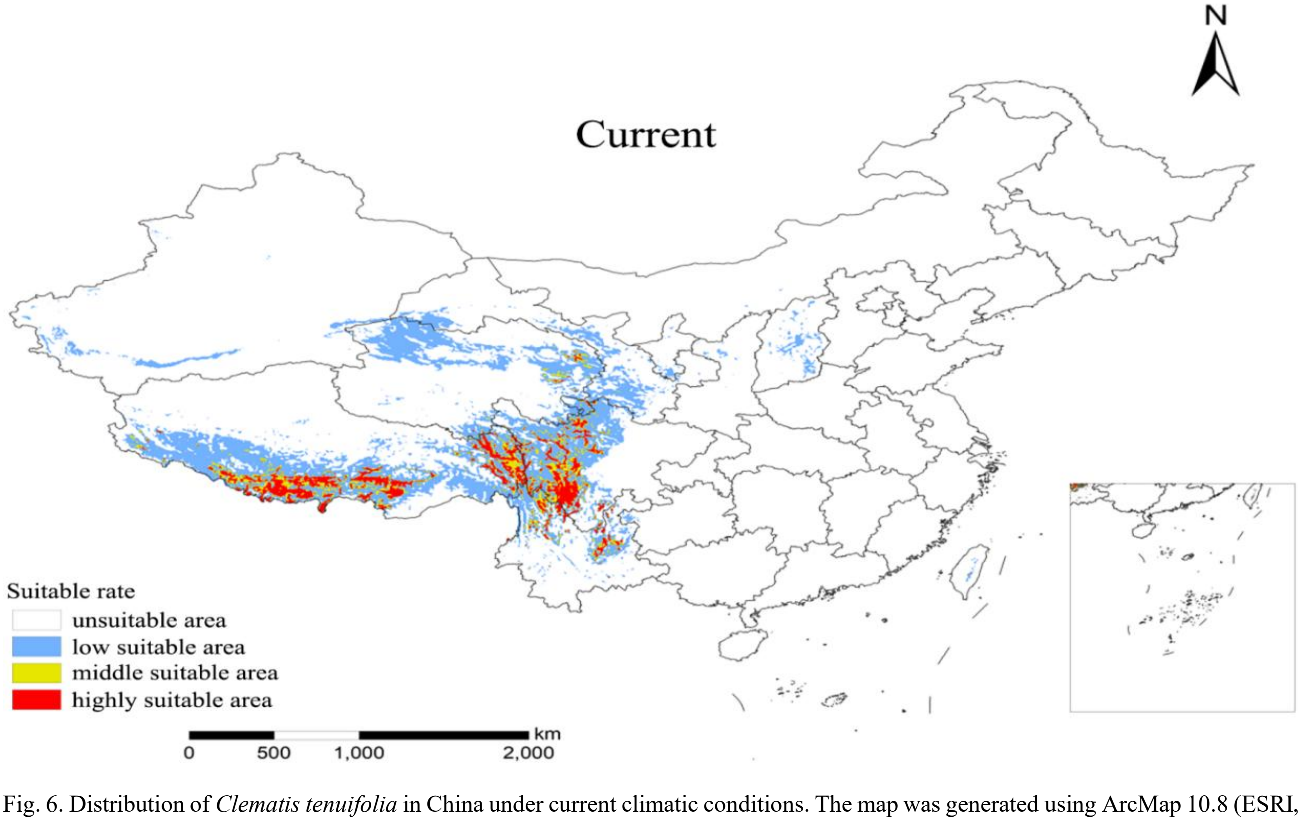

Fig. 6. Distribution of *Clematis tenuifolia* in China under current climatic conditions. The map was generated using ArcMap 10.8 (ESRI, Redlands, CA, USA). Administrative boundaries were sourced from the National Geomatics Center of China (http://www.ngcc.cn) and projected in the WGS84 coordinate system.

Distribution of *Clematis tenuifolia* within China's suitable ecological zones under current climatic conditions: Import the aforementioned cropped ASC-format future climate factors and species location data into the MaxEnt model. The MaxEnt model automatically outputs the average of ten model prediction results, presenting an ecological suitability index ranging from 0 to 1. Higher values indicate greater habitat suitability for *C. tenuifolia*. The minimum training presence log-log threshold (LPT) was employed to define habitat suitability categories (Shcheglovitova & Anderson, 2013; Zhu *et al.*, 2025). Using ArcGIS 10.8 software, the generated suitability map underwent reclassification via manual segmentation with four breakpoints set at: LPT, 0.4, 0.6, and 1. Based on these breakpoints, the suitable habitat zones for *C. tenuifolia* were categorised into four types: unsuitable zone (0–LPT), low suitability zone (LPT–0.4), medium suitability zone (0.4–0.6), and high suitability zone (0.6–1) (Wang *et al.*, 2024).

As shown in Fig. 6 Under current climatic conditions, the potential suitable habitat for *C. tenuifolia* is primarily distributed across Shigatse City, Shannan City, Lhasa City, Nyingchi City, and Qamdo City, as well as Ya'an City, Garzê Tibetan Autonomous Prefecture, Liangshan Yi Autonomous Prefecture in western Sichuan, and Diqing Tibetan Autonomous Prefecture in northern Yunnan. Additionally, small populations are found in Huangnan Tibetan Autonomous Prefecture and Xining City, Qinghai. The total suitable area spans 103.97 × 10^4 km², accounting for approximately 10.83% of the national territory. The highly suitable area for *Clematis tenuifolia* covers 13.12 × 10^4 km², representing 13.14% of the total suitable area. This zone is concentrated in the southern regions of Shigatse City and Lhasa City, as well as the eastern parts of Shannan City and Qamdo City. the southwestern part of the Garze Tibetan Autonomous Prefecture in Sichuan, and the northwestern part of the Liangshan Yi Autonomous Prefecture. Scattered populations are found in Nyingchi City, Ya'an City in Sichuan, and the northwestern part of the Diqing Tibetan Autonomous Prefecture in Yunnan. The moderately suitable area spans 11.75×10^4 km², accounting for 11.77% of the total suitable area. It extends peripherally from the highly suitable zone, primarily distributed across Purang and Cuona counties in Ali, Saga and Angren counties in Shigatse, Angren County in Shigatse, Gongge County and Jiangda County in Nyingchi, Lhasa Prefecture, Lhasa City, Sichuan's Luhuo County and Daofu County, Yunnan's Deqin County and Fugong County, as well as Xining City and Haidong City in Qinghai Province. The low suitability zone covers 79.10×10^4 km², accounting for 79.25% of the total suitable area. It extends further outward from the moderate suitability zone to Zada and Geji counties in the Ali region, Shenqia and Bangong counties in Nagqu City, Sichuan's Aba Tibetan and Qiang Autonomous Prefecture and Mianyang City, as well as Gansu's Longnan City, Qinghai's Mangya City and Delingha City. Overall, the distribution pattern exhibits a trend of expansion from southwest to northeast.

Potential distribution of *Clematis tenuifolia* in China under future climate scenarios: For the 2050s and 2070s projections, soil base saturation (t_bs) and the Human Footprint Index (hfp) were kept constant. We assumed these soil and anthropogenic factors remained static over these decadal scales compared to the rapidly changing macroclimatic variables. Given that the 2050s and 2070s represent the medium- and long-term climate change assessment windows, respectively, they are commonly used in ecological projection studies to avoid short-term natural variability (e.g., 2030s) and the high uncertainty associated with long-term forecasts (e.g., 2090s). This time-frame selection aligns with IPCC assessment report protocols for evaluating ecological impacts (Liu & Shi, 2020; Yang *et al.*, 2024).

This study selected four climate scenarios across two future time periods to project the potential distribution of *C. tenuifolia*. Compared with projections under current climatic conditions, total suitable habitat area decreased under all future scenarios, with low suitability areas also diminishing is shown in Fig. 7 and Table 2. Under the SSP585 scenario for the 2050s, the total suitable habitat area experienced the most significant reduction, decreasing by 44.26 × 10^4 km². Under the SSP370 scenario for the 2070s, the low suitable habitat area showed the greatest decline, decreasing by 30.12 × 10^4 km². Comparing temporal scales, suitable habitat areas decrease in both the 2050s and 2070s relative to current climate conditions. Except for the SSP585 future climate scenario where *C. tenuifolia* shows a slight increase in suitable habitat area compared to the 2050s, all other 2070s suitable habitat areas further diminish relative to the 2050s baseline. Under the SSP245 scenario, the reduction in the *C. tenuifolia*'s suitable habitat area is most pronounced, with a decrease of 8.56 × 10^4 km² compared to the 2050s. This indicates that the *C. tenuifolia* has relatively high environmental requirements for growth. As future climate changes unfold, the population of *C. tenuifolia* is projected to decline continuously.

Table 2. Area of habitat suitability classes for *Clematis tenuifolia* under different time periods (Unit: ×10^4km^2).

Suitable habitats	Comparison indicator	Current	SSP126 2050s	SSP126 2070s	SSP245 2050s	SSP245 2070s	SSP370 2050s	SSP370 2070s	SSP585 2050s	SSP585 2070s
High-suitable habitats	Area/km^2	13.12	7.25	7.97	7.84	5.89	8.02	7.12	4.04	5.28
	Reduction in area		5.87	5.15	5.28	7.23	5.10	6.00	9.08	7.84
Middle-suitable habitats	Area/km^2	11.75	8.79	8.90	8.97	7.77	9.89	9.17	6.44	8.16
	Reduction in area		2.96	2.85	2.78	3.98	1.86	2.58	5.31	3.15
Low-suitable habitats	Area/km^2	79.10	56.52	54.29	57.37	51.96	54.57	48.98	49.23	48.99
	Reduction in area		22.58	24.81	21.73	27.14	24.53	30.12	29.87	30.11
Total-suitable habitats	Area/km^2	103.97	72.56	71.17	74.19	65.63	72.48	65.27	59.71	62.42
	Reduction in area		31.41	32.80	29.78	38.34	31.49	38.70	44.26	41.55

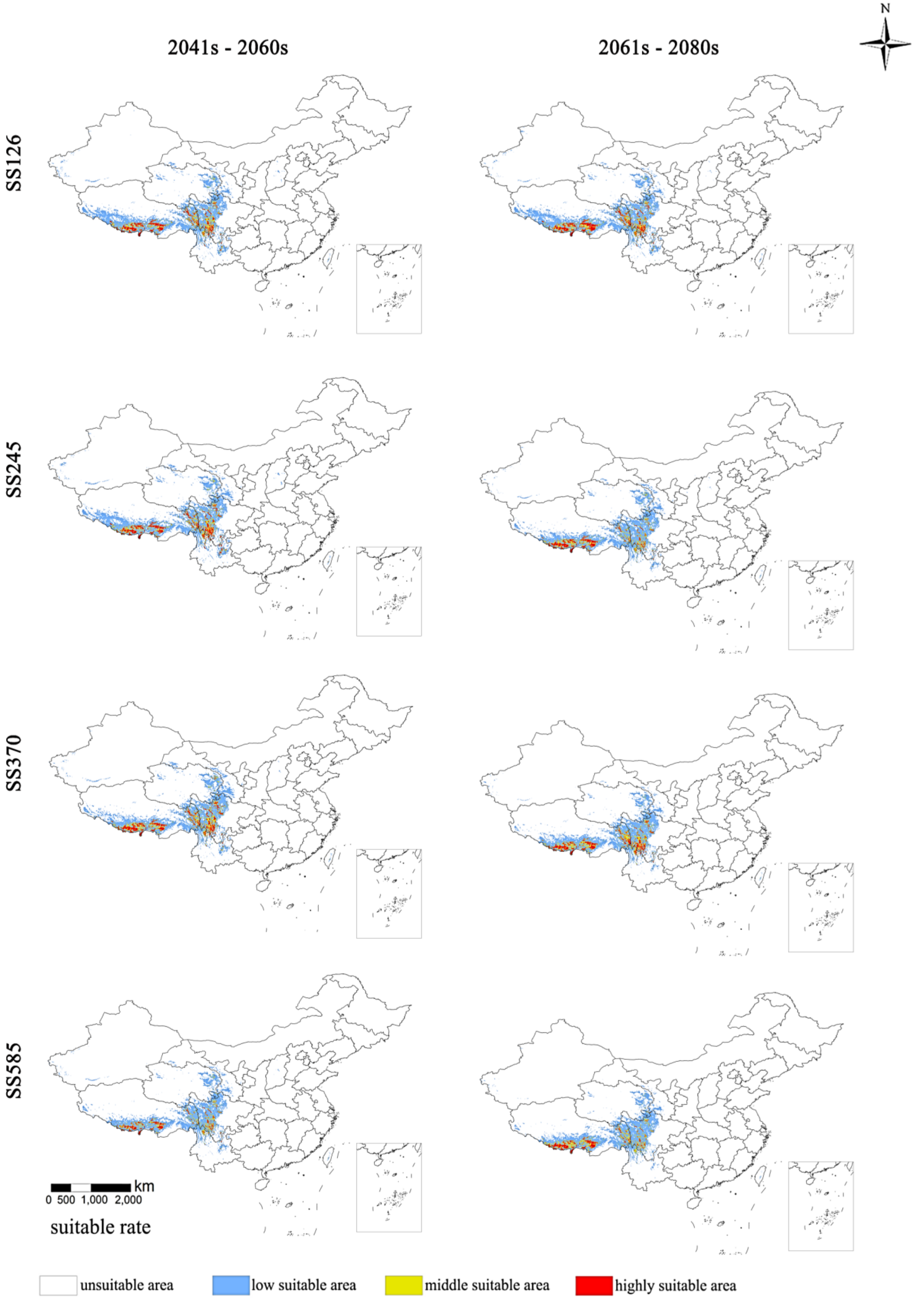

Fig. 7. Changes in the potential habitat of *Clematis tenuifolia* in China under future climate scenarios. The map was generated using ArcMap 10.8 (ESRI, Redlands, CA, USA). Administrative boundaries were sourced from the National Geomatics Center of China (http://www.ngcc.cn) and projected in the WGS84 coordinate system.

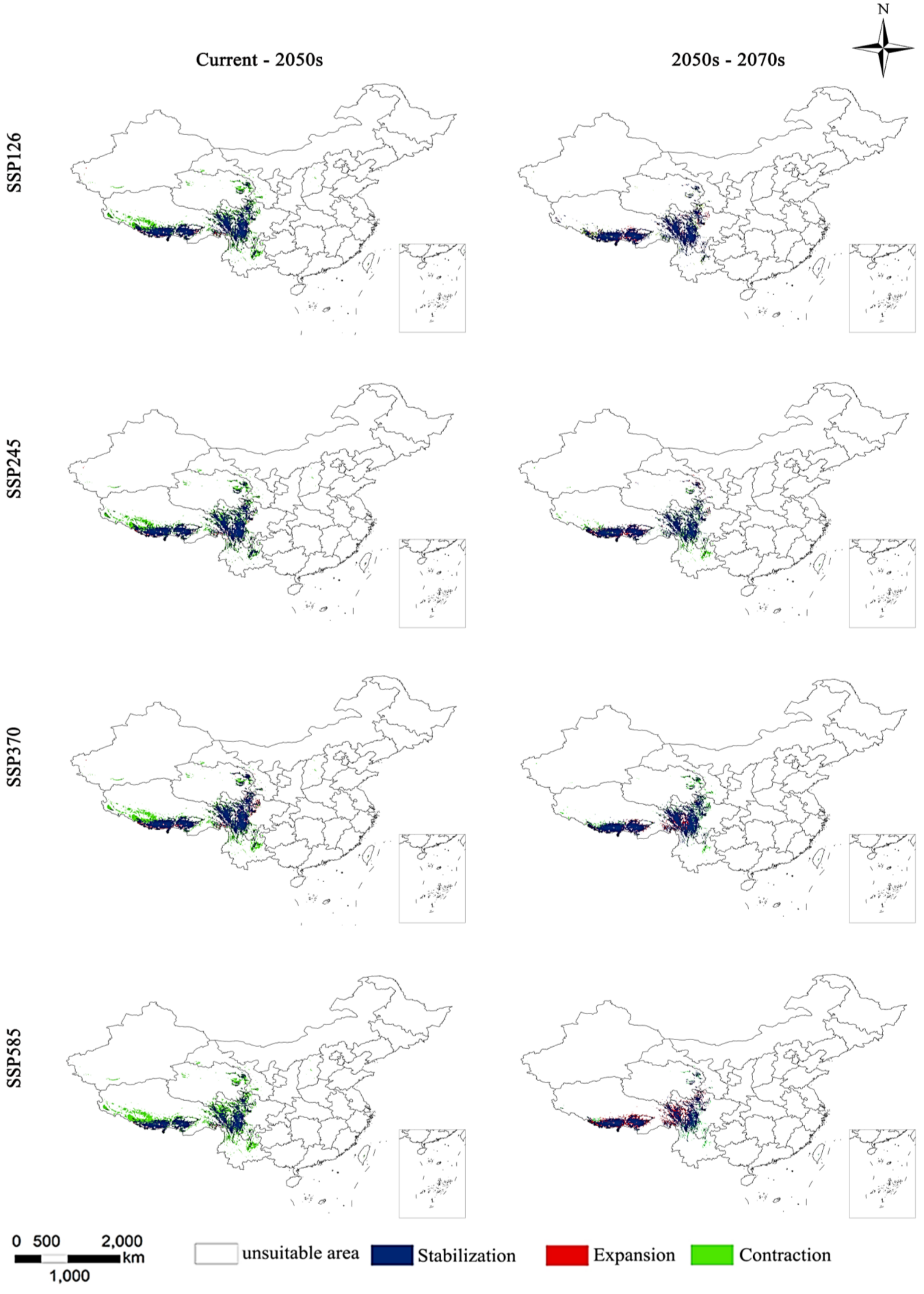

Fig. 8. Changes in the distribution of potential suitable areas for *Clematis tenuifolia* in China under climate change scenarios. The map was generated using ArcMap 10.8 (ESRI, Redlands, CA, USA). Administrative boundaries were sourced from the National Geomatics Center of China (http://www.ngcc.cn) and projected in the WGS84 coordinate system.

Table 3. Changes in the potential suitable area of distribution of *Clematis tenuifolia* under future climate scenarios compared with the current situation(Unit: × 10^4km^2).

Period	Future climate models	Expansion of suitable habitat area	The area of the suitable zone remains unchanged	Shrinking area of suitable zone
2050s	SSP126	1.21	33.97	15.15
	SSP245	1.21	34.93	14.26
	SSP370	2.51	35.01	14.11
	SSP585	0.62	27.20	21.93
2070s	SSP126	2.37	32.60	2.58
	SSP245	1.80	30.08	6.08
	SSP370	2.63	32.87	4.66
	SSP585	6.73	25.41	2.48

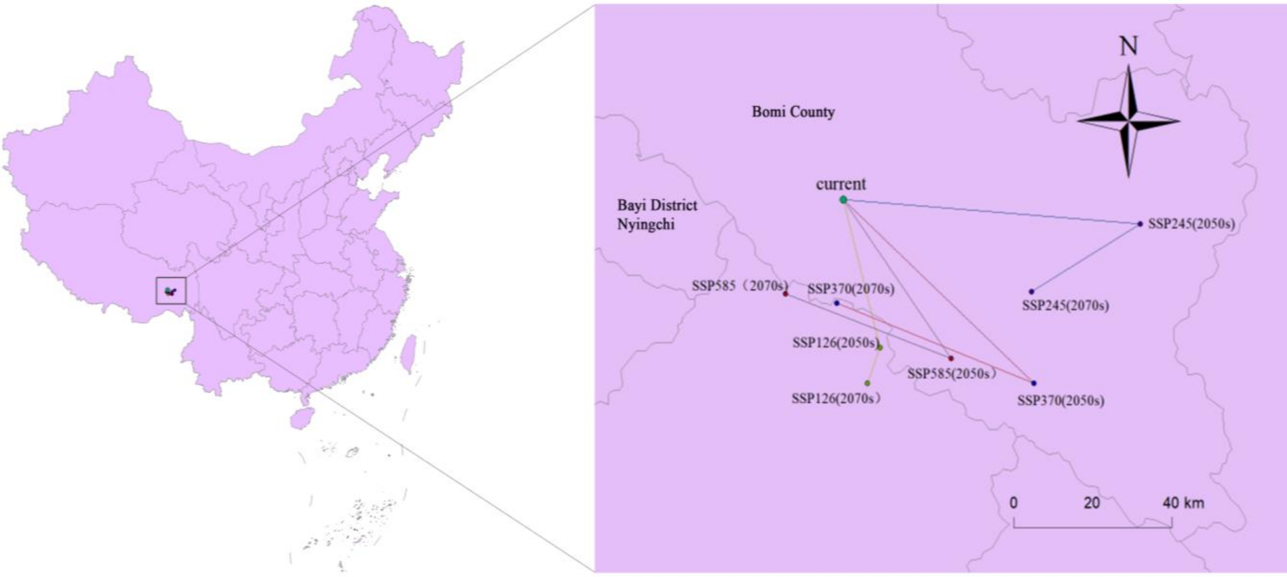

Fig. 9. Changes in the centroid of suitable habitats for Clematis tenuifolia under environmental change scenarios. The map was generated using ArcMap 10.8 (ESRI, Redlands, CA, USA). Administrative boundaries were sourced from the National Geomatics Center of China (http://www.ngcc.cn) and projected in the WGS84 coordinate system.

Spatial pattern changes in the suitable habitat of clematis in tibet under climate change scenarios: The projected shifts in the suitable habitat range of *C. tenuifolia* in China under different future climate change scenarios are presented in Table 3 and Fig. 8 respectively. The primary areas include Yadong County, Kangma County, Gangba County, Dingxue County, Dingri County, and Nyalam County in Shigatse Prefecture; Lazi District and Mozhugongka County in Lhasa City; Naidong District, Qusong County, and Gyachag County in Shannan Prefecture; Lang County and Gongbu Jiangda County in Nyingchi Prefecture; Milin City, and in Qamdo City's Karuo District, Chaya County, and Mangkong County, as well as in Daocheng County, Muli Tibetan Autonomous County, and Jiulong County within Sichuan's Garze Tibetan Autonomous Prefecture. Compared to current conditions, the total suitable habitat area for *C. tenuifolia* in the 2050s will significantly contract under SSP126, SSP245, SSP370, and SSP585. The total suitable habitat area will experience significant contraction across all four scenarios, with limited expansion potential. Under the SSP585 scenario for the 2050s, the expansion of the suitable habitat area for *C. tenuifolia* relative to current levels will be minimal, amounting to just 0.62×10^4 km² (an expansion rate of 1.24%). while the area of contraction reached 21.93×10^4 km², representing a substantial reduction of 44.08%. The contracted zones were primarily distributed across Zada County, Purang County, and Gel County in the Ali region; Lijiang City and the northern part of Kunming City in Yunnan Province; most areas of Huangnan Tibetan Autonomous Prefecture in Qinghai Province; and the northern majority of Garze Tibetan Autonomous Prefecture in Sichuan Province. Compared to the 2050s, by the 2070s the suitable habitat area for *C. tenuifolia* in Tibet will have further contracted under all scenarios except SSP585, where the expansion area exceeds the contraction area. The contracted regions are primarily concentrated in the northern part of Shigatse City in the Tibet Autonomous Region, Kunming City, Qujing City, and the central-northern parts of Chuxiong Yi Autonomous Prefecture in Yunnan Province; the central part of Nujiang Lisu Autonomous Prefecture; and the eastern part of Hainan Tibetan Autonomous Prefecture in Qinghai Province. In summary, the primary areas of change for *C. tenuifolia* encompasses most of northern Shigatse in Tibet, Zada and Purang counties in the Ali region, the northern part of the Garze Tibetan Autonomous Prefecture in Sichuan, the area north of the Nujiang Lisu Autonomous Prefecture in Yunnan, and the eastern part of the Hainan Tibetan Autonomous Prefecture in Qinghai.

Shifting the center of gravity of suitable habitats for *Clematis tenuifolia* under climate change scenarios: Projected shifts in the distribution centroid of *Clematis* *tenuifolia* under 4 carbon emission scenarios (SSP126, SSP245, SSP370, and SSP585) are predominantly concentrated within Bomi County, Nyingchi City, Tibet Autonomous Region, with minor deviations toward the Bomi–Medog boundary is shown in Fig. 9. Two distinct temporal patterns of centroid migration are observed. From the present to the 2050s, the centroid consistently shifts southeastward. However, from the 2050s to the 2070s, the trajectories diverge: the centroid continues southwestward under SSP126 and SSP245, but reverses northwestward under SSP370 and SSP585.

The current distribution centroid is located in Bomi County (95°57′36″E, 29°49′43″N). Under the SSP126 scenario, the centroid migrates 35.15 km southeastward to Medog County by the 2050s, and an additional 8.87 km southwestward by the 2070s. Under SSP245, the centroid shifts 64.55 km southeast to Kangyu Township (Bomi County) by the 2050s, followed by a 53.69 km southwestward shift to Duoji Township (Bomi County) by the 2070s.

In contrast, under SSP370 and SSP585, the centroid initially shifts southeastward in the 2050s—76.50 km to Songzong Township (SSP370) and 45.77 km to Zamu Township (SSP585)—but then reverses direction, migrating northwestward by 31.82 km and 44.99 km, respectively, reaching Medog County by the 2070s.

All migration distances were calculated as great-circle distances using the WGS84 ellipsoid. These results reveal a transitional pattern of "initial southeastward shift followed by divergent migration" with all centroids remaining within Nyingchi City. This indicates that the southeastern Tibetan Plateau will likely remain the ecological core zone for *Clematis tenuifolia* under future climate change.

Discussion

In this study, MaxEnt model parameters - regularization multiplier (RM = 3) and feature class (FC = LQ) — were optimized using the ENMeval package, which significantly reduced the risk of overfitting and yielded a high predictive accuracy (AUC = 0.989) (Zhang *et al.*, 2023; Xie *et al.*, 2025). In comparison to the standard MaxEnt setup, the optimized version was a better approximation of the ecological niche requirements of *C. tenuifolia*, especially in its responsiveness to temperature-related variables, where bio3, bio8, and bio9 contributed 84.4 to model performance. These results agree with the current research findings on the endangered species like *Rhodiola crenulata*, where optimized MaxEnt models have shown better predictive reliability. This emphasizes the significance of parameter calibration in the case of species that have few occurrence records (Lye *et al.*, 2013; Anon., 2022). However, the reliance on 46 occurrence records presents a potential limitation. Given the vastness and topographic complexity of the Qinghai-Tibet Plateau, these records may not completely capture the species' entire fundamental niche. Therefore, our predictions represent more suitable habitats and should not be over-generalized across the entire region.

As the isothermally (bio3) grew, the habitat suitability of *C. tenuifolia* grew as well, which implies the ecological fitness of this plant to the significant diurnal variation in temperature and high intensity of solar radiation in alpine habitats. The maximum response at 7°C of the mean temperature of the wettest quarter (bio8) and the minimum response at −1°C of the mean temperature of the driest quarter (bio9) indicates that moderate and humid winters and cool summers are essential to the survival of this species conditions that are similar to those of a monsoon-driven climate in the southeast area of the Qinghai-Tibetan Plateau. Furthermore, research by Li *et al*., (2024) on *Clematis* species indicates the peak occurrence at approximately 7°C during the wettest season strongly aligns with the physiological traits of alpine *Clematis* species. This moderate thermal window optimally supports root metabolism and nutrient uptake during the active growing season, whereas higher temperatures may induce heat stress, accelerate excessive transpiration, or trigger root diseases in shallow mountain soils. (Li *et al.*, 2024a; Li *et al.*, 2024b). Additionally, this thermal response reflects the species' physiological requirement to regulate root mineral absorption, a critical process in nutrient-poor alpine soils under which physiological processes are very sensitive to mineral presence (You *et al.*, 2018). Conversely, the human footprint indicator (hfp) indicated that there was a rather small contribution (3.5%), which means that there is a small amount of human disturbances in the species distribution area at present. Nevertheless, further urban growth and infrastructure planning could increase habitat fragmentation especially in marginal habitats (Han *et al.*, 2022; Sofi *et al.*, 2023).

The considerable decrease of appropriate habitats in all future climate scenarios (including 29.78×10^4 km^2–44.26×10^4 km^2 by the 2070s) can be largely ascribed to the impact of warming on the alteration of temperature thresholds. Specifically, the SSP585 scenario predicts that winter temperatures (bio9) will exceed the species tolerable level (−1°C) in the driest quarter, which will lead to a rapid decline of habitat in the peripheral areas of northwestern Sichuan and northern Yunnan- this leads to a reduction of up to 44.08%. This significant reduction in total area will inevitably lead to severe habitat fragmentation. As suitable habitats shrink into isolated patches, restricted pollen and seed dispersal will hinder gene flow. Over time, this isolation threatens the genetic diversity and long-term viability of the species, posing a serious ecological risk that extends beyond the mere loss of total acreage. While localized expansions are projected in southeastern Tibet due to increased warming and humidification, such gains are outweighed by widespread thermal stress and intensified drought elsewhere. For example, mean temperatures in the wettest quarter (bio8) are projected to surpass 7°C in the Ali region, a threshold beyond which regeneration is inhibited. The species distribution centroid is projected to shift southeastward by 35–77 km, stabilizing near Bomi and Medog—areas characterized by consistent humidity and moderated temperatures due to Indian Ocean monsoon influence. These findings underscore the potential of southeastern Tibet to serve as a future climatic refuge for *C. tenuifolia* under ongoing climate change (Li *et al.*, 2024a).

To address this threat, there is an urgent need to implement a set of integrated conservation measures, alongwith pharmacological studies. First, the identified 'climatic refuge' in the Bomi-Medog region must be prioritized. We suggest establishing a specialized nature reserve and ecological redline zone around its core coordinates (approximately 95°15′–96°00′E, 29°15′–29°55′N) to make conservation actions more actionable and targeted for local authorities. The second point is that the monitoring of existing populations in southern Tibet (e.g., southern Shigatse and Shannan) and southwestern Sichuan (e.g., southwestern Garzê Prefecture) should be strengthened and integrated into the national park system.

It is proposed to build a cold-storage germplasm bank to save seeds and living specimens of populations undergoing habitat loss (e.g., Ali, northern Yunnan, and southern Qinghai) in either Lhasa or Nyingchi. Together with the Tibetan medicine research centers, it must be started to test artificial cultivation to select heat-tolerant genotypes and implement pilot-scale bionic cultivation in the climatically suitable regions of southeastern Tibet. Local extinction in areas suffering extreme contraction (e.g. Pulan County in Ali and northern Garze) could be postponed by introducing microclimate measures like artificial humidification and shade (Brambilla *et al.*, 2022).

Conclusion

The main distribution of *C. tenuifolia* (13.12×10^4 km²) under the present climatic conditions is in the south of Tibet (Shigatse and Shannan) and southwest of Sichuan. The distribution is highly influenced by the climatic factors, including isothermally (bio3), the average temperature of the wettest quarter (bio8), and the average temperature of the driest quarter (bio9), which all account to more than 84% of the habitat suitability model—emphasizing the fact that the species is ecologically much dependent on the alpine monsoon climate.

In future climate projections to the 2070s, it is predicted that the total area of suitable habitat will decrease by 30–44% and highly suitable area will reduce by 39–69% especially in the SSP585 scenario. The main contraction hotspots are located on the Ali plateau and in ecotonal areas of Sichuan, Yunnan, and Tibet, whereas small-scale expansions in southeastern Tibet do not compensate for the overall loss. Taken together, these results indicate that *C. tenuifolia* populations are probably going to experience a dramatic decrease due to the current global warming. Subsequently, although developing up-to-date pharmacological studies of the species, it is necessary to pay the same attention to the conservation of this endemic species and the sustainable use of it.

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