

Article

Prediction of Suitable Habitats for Tibetan Medicinal *Gentiana* Plants of Jieji- and Bangjian-Type *Gentianas* Based on the MaxEnt Model

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Abstract

The Gentianaceae family, particularly the genus *Gentiana*, is predominantly distributed across the Qinghai-Tibet Plateau and its adjacent regions. As a widely used traditional medicinal resource in Tibetan medicine, these plants possess diverse pharmacological activities, including heat-clearing, detoxification, antibacterial, antitumor, and immunomodulatory effects. Based on their medicinal properties and traditional use, *Gentiana* plants in Tibetan medicine are classified into two major groups: Bangjian-type and Jieji-type plants. In the context of intensifying climate change, understanding the responses of these two Tibetan medicinal plant groups to future climate scenarios is of great significance for the effective conservation and sustainable utilization of *Gentiana* resources. In this study, distribution data from 355 Bangjian-type *Gentiana* and 417 Jieji-type *Gentiana* medicinal plants, along with 12 selected key environmental variables, were used to predict their potential suitable habitats under three climate scenarios—SSP126 (low-carbon), SSP245 (medium-carbon), and SSP585 (high-carbon)—across the present and four future time periods, using the Maximum Entropy (MaxEnt) model. The average AUC values of the Bangjian-type and Jieji-type *Gentiana* models were 0.925 and 0.924, respectively, indicating high predictive reliability. Under current climatic conditions, the estimated suitable habitat areas for Bangjian-type and Jieji-type *Gentiana* plants are $208.86 \times 10^4 \text{ km}^2$ and $211.70 \times 10^4 \text{ km}^2$, respectively. The most suitable regions are primarily located in the South-eastern Qinghai-Tibet Plateau, with distribution centroids in Jiangda County, Chamdo, Xizang, China. Altitude was the most influential environmental factor shaping their distribution, followed by precipitation and temperature. In the future, climate change is expected to reduce the overall habitat of Jieji-type *Gentiana*, with only moderate expansion projected in Central China under the SSP126 scenario. In contrast, Bangjian-type *Gentiana* is projected to experience habitat expansion in most climate scenarios, with only minor contractions under SSP585. These findings highlight the potential shifts in the distribution of *Gentiana* resources under various climate scenarios and provide a scientific basis for developing conservation strategies for Tibetan medicinal plants in the face of climate change.

Keywords: *Gentiana*; Tibetan medicinal plants; habitat suitability modeling; climate change; MaxEnt model



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1. Introduction

China's exceptional biodiversity, surpassing that of comparable latitudes, underscores its critical role in the global ecological landscape [1,2]. However, this richness is imperiled by global climate change, a process that disrupts plant ranges and undermines ecological stability through unpredictable species movements [3,4]. The predicament of the Qinghai–Tibet Plateau highlights this susceptibility. This region, which is home to great plant diversity and precious Tibetan medicinal resources, is witnessing a rapid loss of unique species due to climate change, as demonstrated by altered phenology and diminishing habitats [5,6]. Therefore, systematically assessing future shifts in suitable habitats for medicinal plants is crucial, forming the basis for effective conservation, sustainable resource management, and the preservation of ecosystem services.

The Gentianaceae are widely distributed worldwide. In China, the family comprises 15 genera and approximately 410 species, of which 251 are endemic. The genus *Gentiana* is the largest, containing about 230 species. The Qinghai–Tibet Plateau and its neighboring regions represent the center of *Gentiana* diversity. *Gentiana* species have been used in Tibetan medicine for centuries [7–9]. The medicinal use of their dried flowers or whole flowering plants—for clearing heat, detoxification, and anti-inflammatory purposes—is documented in foundational Classical Tibetan medical texts such as The Four Medical Tantras, Materia Medica of Tibetan Medicine, Crystal Pearl Materia Medica, and Crystal Mirror Materia Medica.

In Tibetan medicine, medicinal *Gentiana* species are historically categorized into two primary groups—“Jieji” and “Bangjian”—based on their therapeutic effects and physical qualities. The Jieji group primarily corresponds to the *Gentiana* sect. *Cruciata*, while the Bangjian group mainly includes species of sect. *Monopodiae* and sect. *Frigida* [10–12]. This traditional classification system is based on differences in medicinal efficacy (e.g., heat-clearing, detoxifying, or anti-inflammatory functions) and morphological traits (such as flower color and root morphology). It forms the basis of Tibetan medical usage and is closely linked to the ecological niches and distribution patterns of these species.

Representative species of the Jieji group are perennial herbs with slightly fleshy, fibrous, conical, or cylindrical taproots. The plant base is surrounded by persistent leaf sheaths and has a well-developed rosette of basal leaves, with flowers appearing large to medium-sized (Figure 1). According to flower color, the Jieji group is divided into white-flowered (Jieji Gabo, mainly *G. straminea* Maxim) and black-flowered (Jieji Nabo, mainly *G. crassicaulis* Duthie ex Burkill) types. White-flowered species are traditionally used to treat heat-related syndromes, while black-flowered species are used for “yellow water” disease. Ecologically, Jieji species are typically found in riverbanks, shrublands, and forest understories [8,10,13].

Bangjian-type plants, including sect. *Monopodiae* and sect. *Frigida*. Sect. *Monopodiae* species are perennial herbs with residual stems or membranous leaf sheaths at the base, shallowly lobed corollas with prominent plicae, and generally large flowers. Sect. *Frigida* species are characterized by short rhizomes and fibrous roots, a well-developed basal leaf rosette, and monocarpic flowering branches that wither after blooming; these flowers are medium to large. Bangjian species can be classified by flower color into white (Bangjian Gabo, e.g., *G. purdomii* C. Marquand, *G. szechenyii* Kanitz), blue (Bangjian Wenbo, e.g., *G. veitchiorum* Hemsl, *G. lawrencei* var. *farreri* (Balf. f.) T. N. Ho), and variegated (Bangjian Nabo, e.g., *G. nubigena* Edgew, *G. futtereri* Diels & Gilg). Pharmacologically, they are used for detoxification, various heat-related syndromes, and throat inflammation, and ecologically, they inhabit alpine meadows, marshes, gravel slopes, and upland grasslands [8,14,15].



Figure 1. Representative plants of Bangjian-type and Jieji-type *Gentiana*, illustrating the typical morphology of each group. (a) and (b) show Bangjian-type species *G. purdomii* C. Marquand and *G. veitchiorum* Hemsl, respectively; (c) and (d) show Jieji-type species *G. straminea* Maxim and *G. crassicaulis* Duthie ex Burkill, respectively. Photos were taken by SU Hao. Voucher specimens are deposited in the Herbarium of College of Ecology and Environment, Xizang University, with voucher numbers: (a) MX5401022024072; (b) LYZ404212024006; (c) MH5403232024022; (d) CJ5404252024013. The original specimen label in Chinese is visible in the image as an integral part of the historical record.

The classification of Jieji and Bangjian, based on morphology, flower color, and pharmacological use, is closely linked to ecology and environmental distribution. Species of different categories occupy distinct altitudes and habitat types. These ecological features provide a rationale for modeling their potentially suitable habitats. By analyzing the potential distribution of Jieji and Bangjian species, this study aims to reveal ecological preferences and inform the conservation and sustainable use of Tibetan medicinal plant resources.

Despite their high medicinal value, two major challenges exist to the long-term use of *Gentiana*: first, the primary medicinal part—the flowers—is primarily harvested from wild populations, resulting in a limited supply; second, the botanical origins of commercial *Gentiana* are frequently misidentified. While Tibetan medicine theoretically distinguishes between “Jieji” and “Bangjian” types, the indiscriminate substitution of species in practice compromises product quality. Therefore, systematic studies on taxonomy, resource distribution, and habitat prediction are crucial for identifying dominant medicinal species and conserving biodiversity. Nevertheless, studies on habitat suitability prediction for these two Tibetan medicinal categories remain scarce.

Species Distribution Models (SDMs) are essential instruments in ecology and conservation, forecasting optimal habitats for species by evaluating the correlation between species occurrence and environmental variables. They offer a comprehensive framework for forecasting habitat suitability in the context of climate change and are extensively utilized in biodiversity evaluation and the conservation of medicinal plants [16,17]. The Maximum Entropy (MaxEnt) model is a prominent and widely used species distribution modeling technique. This ecological niche modeling method conceptualizes a species and its environment as an integrated system. Based on the maximum entropy principle, it determines the most probable species distribution that maximizes entropy given environmental restrictions, thereby inferring the species–environment link and accurately forecasting prospective geographic ranges [18,19]. Due to its computational speed and dependable performance with small sample numbers, MaxEnt is highly successful for simulating dy-

namic shifts in suitable habitats, making it particularly applicable to endangered species and widely utilized in studies on Tibetan medicinal plants [20,21].

This study employs the Maximum Entropy (MaxEnt) model to predict the suitable habitats of fourteen medicinal *Gentiana* species, comprising eight “Bangjian” types (*G. veitchiorum* Hemsl, *G. lawrencei* var. *farreri* (Balf. f.) T. N. Ho, *G. purdomii* C. Marquand, *G. obconica* T. N. Ho, *G. erectosepala* T. N. Ho, *G. stipitata* Edgew, *G. szechenyii* Kanitz, and *G. sino-ornata* Balf. f.) and six “Jieji” types (*G. lhasica* Burkill, *G. waltonii* Burkill, *G. tibetica* King ex Hook. f., *G. crassicaulis* Duthie ex Burkill, *G. straminea* Maxim, and *G. robusta* King ex Hook. f.). Among the Bangjian species, *G. obconica* T. N. Ho and *G. erectosepala* T. N. Ho are endemic to Xizang and are typical alpine plants restricted to high-elevation habitats. Their narrow spread makes them highly sensitive to environmental changes. In the Jieji group, *G. lhasica* Burkill is listed as Near Threatened, and *G. waltonii* Burkill is classed as Critically Endangered, and both taxa have very limited and fragmented populations. Understanding how their suitable habitats may move under climate change is therefore important for their long-term conservation. Specifically, the study intends to (1) evaluate the links and variances between the current regional distributions of these *Gentiana* species and major environmental parameters and (2) predict probable range changes for distinct *Gentiana* taxa under future climatic conditions. The findings are likely to provide scientific support for the sustainable use and protection of *Gentiana*-derived Tibetan medicinal resources.

2. Materials and Methods

2.1. Biological Characteristics of the Main Source Species of “Jieji” and “Bangjian” Types

Representative herbarium specimens and field photos of the studied species are shown in Figure 1 and were used to verify the classification of species into the Jieji or Bangjian groups. Species classification was based on morphological characteristics, flower color, and literature references [10–12], as detailed in the Introduction.

2.2. Distribution Data Acquisition and Filtering

We obtained distribution records of Tibetan medicinal *Gentiana* species from the Chinese Virtual Herbarium (CVH, <http://www.cvh.org.cn> (accessed on 16 September 2025)), the National Specimen Information Infrastructure (NSII, <http://www.nsii.org.cn> (accessed on 16 September 2025)), the Global Biodiversity Information Facility (GBIF, <https://www.gbif.org/zh/> (accessed on 29 May 2025)), and published literature [22–25]. We additionally conducted field investigations in Xizang from August to October 2024, resulting in a total of 693 Bangjian-type and 623 Jieji-type populations being recorded (Figure 2). To prevent model overfitting, we spatially filtered the records in R, merging those within each 5×5 km grid. This process yielded a final set of 355 Bangjian and 417 Jieji populations for model construction.

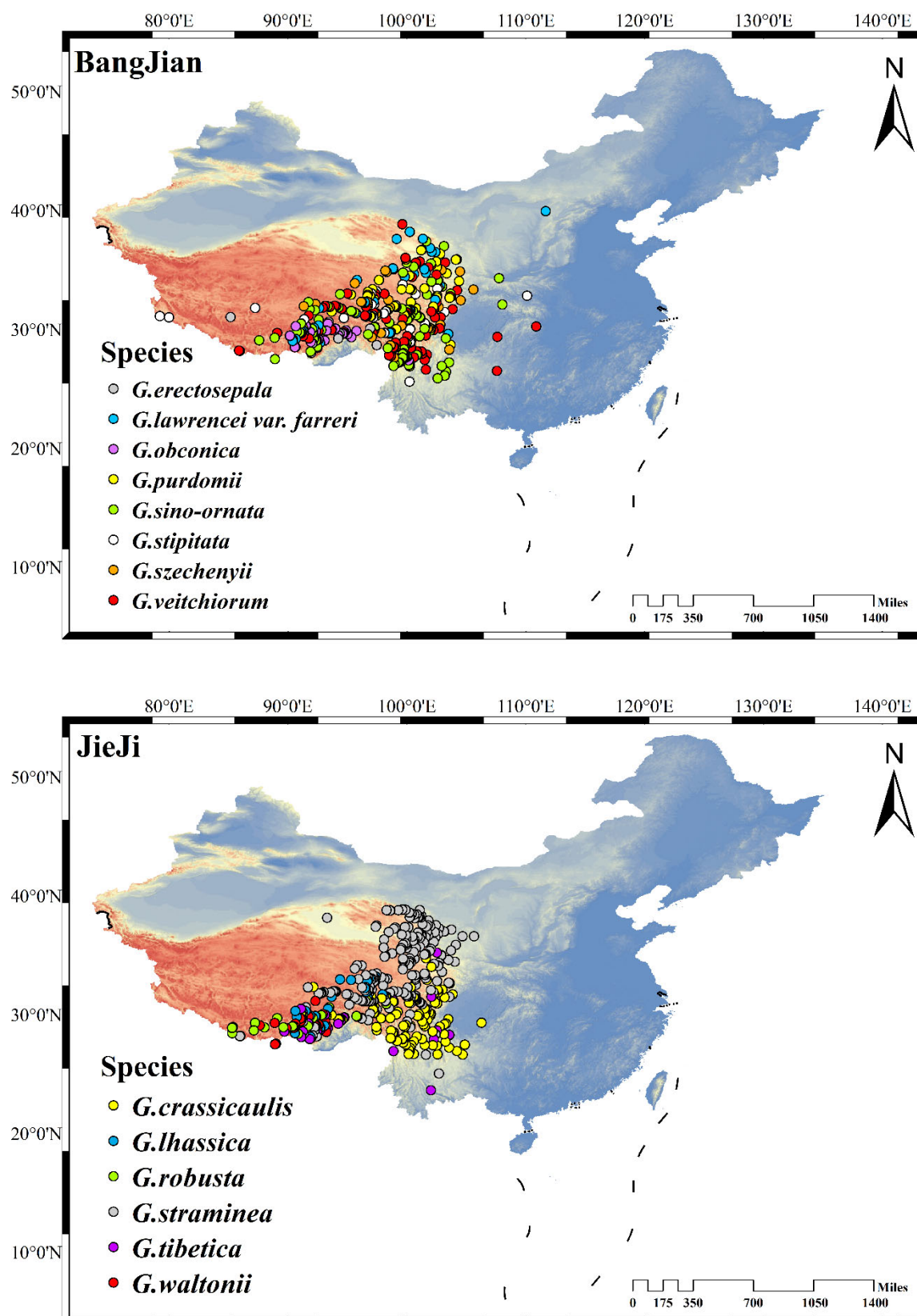


Figure 2. Distribution Point of Bangjian-type and Jieji-type plants in China.

Several species, such as *G. erectosepala* T. N. Ho, *G. lhassica* Burkill, and *G. waltonii* Burkill, had fewer than 30 raw records, and even fewer after spatial filtering, approaching the minimum threshold for reliable MaxEnt modeling (10–20 records) [26]. To maintain model robustness, we therefore conducted grouped modeling based on the

traditional Tibetan medicinal classification (Bangjian vs. Jieji) [27], which allows assessment of climate-driven habitat shifts at the level relevant to medicinal use.

2.3. Acquisition and Selection of Environmental Variables

We obtained 19 bioclimatic variables and elevation from the WorldClim database (<https://www.worldclim.org/> (accessed on 29 May 2025)) and 18 soil variables from the FAO World Soil Database's China soil dataset (<https://www.fao.org/> (accessed on 29 May 2025)). Future climate data were derived from the BCC-CSM2-MR model under three emission scenarios (SSP126, SSP245, SSP585) [28]. All layers were resampled to 2.5 arc-minutes. To avoid overfitting, we refined the variable set as follows: First, we ran MaxEnt 10 times with all 38 variables and removed those with consistently low contributions (<0.1). Subsequently, we performed Spearman correlation analysis on the remaining variables and retained only the variable with higher ecological relevance from any correlated pair ($|r| > 0.8$). The resulting dominant variables and their contributions are presented in Table 1.

Table 1. Contribution of Dominant Environmental Variables to the Habitat Suitability of Tibetan Medicinal *Gentiana* Based on the MaxEnt Model.

Abbreviation	Bio-Climatic Variables	Bangjian		Jieji	
		Percent Contribution	Permutation Importance	Percent Contribution	Permutation Importance
Elevation	Elevation	44.5	5.9	34	5.7
bio3	Isothermality	12.1	22.1	30.9	50.9
bio12	Annual Precipitation	NA	NA	20.6	28.6
bio11	Mean Temperature of Coldest Quarter	7	7.6	5.2	5
bio4	Temperature Seasonality	3.3	16.9	4.3	8.5
bio18	Precipitation of Warmest Quarter	29.1	43.9	NA	NA
T_CACO3	Carbonate or lime content	NA	NA	3.2	0.8
T_BS	Basic Saturation	NA	NA	1.8	0.5
T_ESP	Exchangeable sodium salt	NA	NA	0.1	0.1
T_CEC_CLAY	Cation Exchange Capacity of Clayey Soils	2.9	3	NA	NA
T_SILT	Silt content	0.8	0.3	NA	NA
T_PH_H2O	pH level	0.3	0.2	NA	NA

2.4. Model Parameter Optimization

We used the ENMeval package (version 2.0.5) in R [29] to optimize key MaxEnt parameters, such as the feature classes (FC) and the regularization multiplier (RM), to reduce overfitting and make the model more reliable. We tried six different types of FC (L, H, LQ, LQH, LQHP, and LQHPT) and RM values from 0 to 4, with 0.5 increments. Cross-validation was used to test each model configuration, and the parameter set with a delta AICc value of zero was chosen as the best one for building the final model. MaxEnt also had a 75% occurrence point rate for training, a 25% occurrence point rate for validation, a maximum of 10 iterations, 10,000 background points, and a logistic output format. The area under the receiver operating characteristic curve (AUC) was used to measure how well the model worked. AUC values were interpreted as follows: 0.7–0.8 for moderate, 0.8–0.9 for adequate performance, and 0.9–1.0 for excellent predictive performance [30].

2.5. Data Processing

All data processing, habitat suitability classification, and visualization were conducted in R. The raw habitat suitability indices generated by MaxEnt were imported and reclassified into four levels—unsuitability, low, medium, and high suitability area—using the Natural Breaks (Jenks) method (Table 2).

Table 2. Suitability Index Grading Based on the Natural Breaks Method.

Category	Unsuitability Area	Low Suitability Area	Medium Suitability Area	High Suitability Area
Bangjian	0–0.068	0.068–0.2501	0.2501–0.4881	0.4881–0.8424
Jieji	0–0.0707	0.0707–0.2423	0.2423–0.4828	0.4828–0.8280

Using the “raster” package (version 3.6.32) in R, the current habitat suitability distribution of *Gentiana* species was analyzed, and the dynamic changes in suitable areas were projected under 12 future climate scenarios [31]. The “geosphere” package (version 1.5.20) was employed to calculate the centroid shift distances of Tibetan medicinal *Gentiana* species under different climate scenarios, thereby identifying the current and projected suitable areas of Bangjian and Jieji groups [32].

3. Results

3.1. Model Optimization and Evaluation Results

The Maximum Entropy (MaxEnt) model displayed good accuracy in finding ideal habitats for the medicinal *Gentiana* species, with mean test AUC values of 0.925 for the Bangjian group and 0.924 for Jieji. These habitat predictions, based on species occurrence records and screened environmental variables, utilized group-specific parameter values modified for each group (Bangjian: FC = LQH, RM = 0.5; Jieji: FC = LQHPT, RM = 1.5).

3.2. Environmental Variables and Response Curves

The Jackknife test identified the dominant environmental controls on the distribution of the Tibetan medicinal *Gentiana* species (Figures 3 and 4). Elevation was the most influential variable for both groups. Regarding climate, isothermality (bio3) was a key temperature variable for both, while precipitation of the warmest quarter (bio18) and annual precipitation (bio12) were primary for Bangjian and Jieji, respectively. For soil properties, cation exchange capacity (T_CEC_CLAY) and carbonate content (T_CACO3) were associated with Bangjian and Jieji, respectively.

Suitable habitats (occurrence probability > 0.5) were characterized by distinct environmental ranges. The Bangjian group primarily occurred at an altitude of 3003.6–4640.5 m, with optimal isothermality of 38.7–47.8, warmest-quarter precipitation of 274.5–396.7 mm, and cation exchange capacity of 66.3–87.2. In contrast, the Jieji group occupied elevations of 2835.7–4523.2 m, with optimal isothermality of 38.5–47.3, annual precipitation of 311.9–825.9 mm, and carbonate content of 0.2–3.8. Overall, while altitude was the foremost factor, Bangjian distribution was more strongly governed by precipitation, whereas Jieji was more sensitive to temperature variation (Table 1, Figure 3).

3.3. Suitable Habitat Area

Under current climatic conditions, the potentially suitable area was similar for both groups, with Bangjian-type *Gentiana* covering $204.86 \times 10^4 \text{ km}^2$ and Jieji-type covering $211.70 \times 10^4 \text{ km}^2$. Both were predominantly concentrated on the Qinghai–Tibet Plateau and its periphery. The high-suitability zone for Bangjian ($55.91 \times 10^4 \text{ km}^2$, 27.3%) was primarily located in Western Sichuan and Southeastern Xizang, whereas for Jieji ($53.90 \times 10^4 \text{ km}^2$, 25.5%), it was found in Western Sichuan, Southern Xizang, and Eastern Qinghai. The medium-suitability area was more extensive for Jieji ($63.61 \times 10^4 \text{ km}^2$, 30.0%) than for Bangjian ($51.92 \times 10^4 \text{ km}^2$, 25.3%), with core distributions across Xizang, Qinghai, and Sichuan for both. Conversely, Bangjian had a larger proportion of low-suitability area ($97.03 \times 10^4 \text{ km}^2$, 47.4%) compared to Jieji ($94.19 \times 10^4 \text{ km}^2$, 44.5%), with both extending into Gansu and Yunnan provinces (Figure 5).

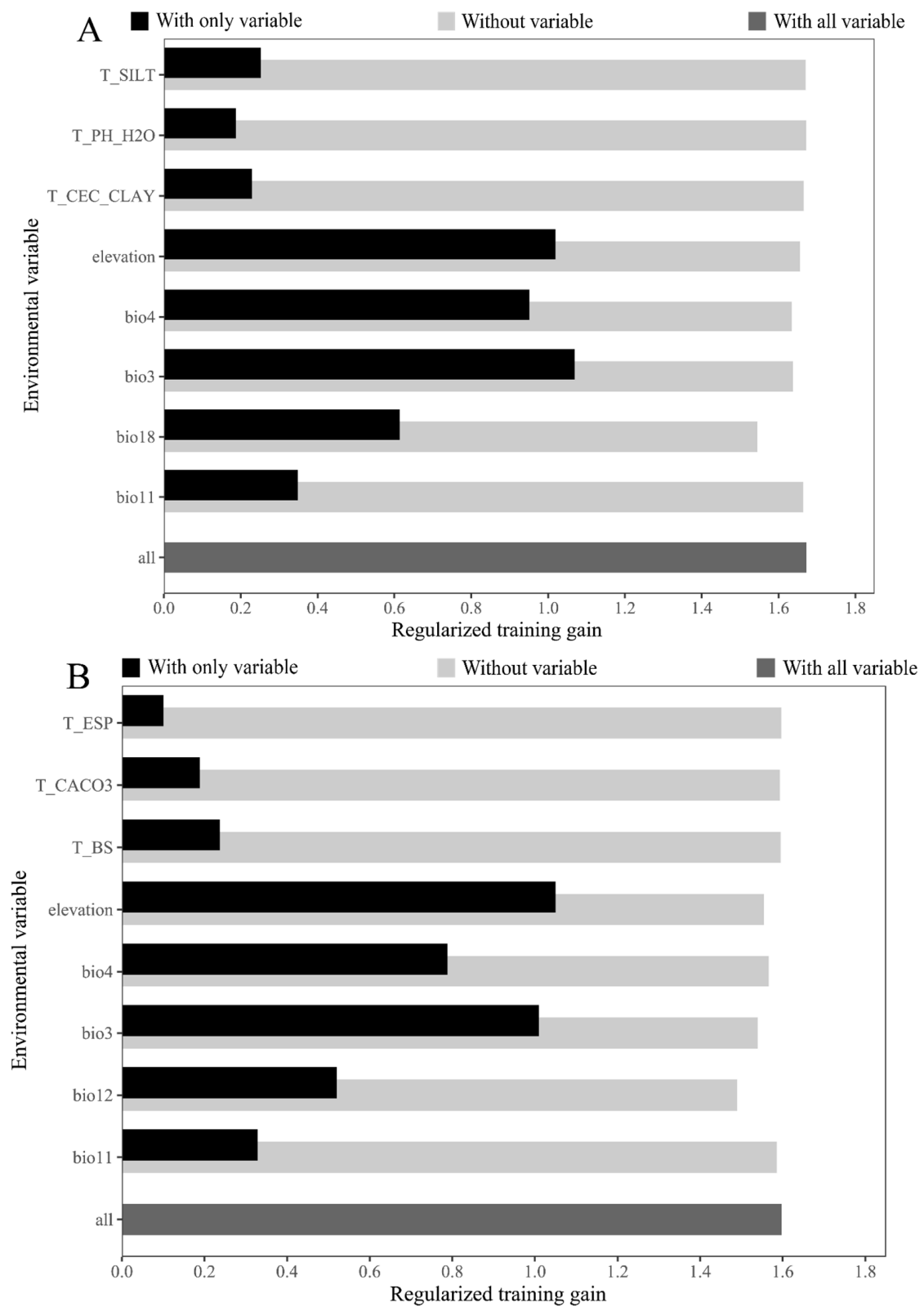


Figure 3. Regularized Training Gain Curves: Bangjian (A); Jieji (B).

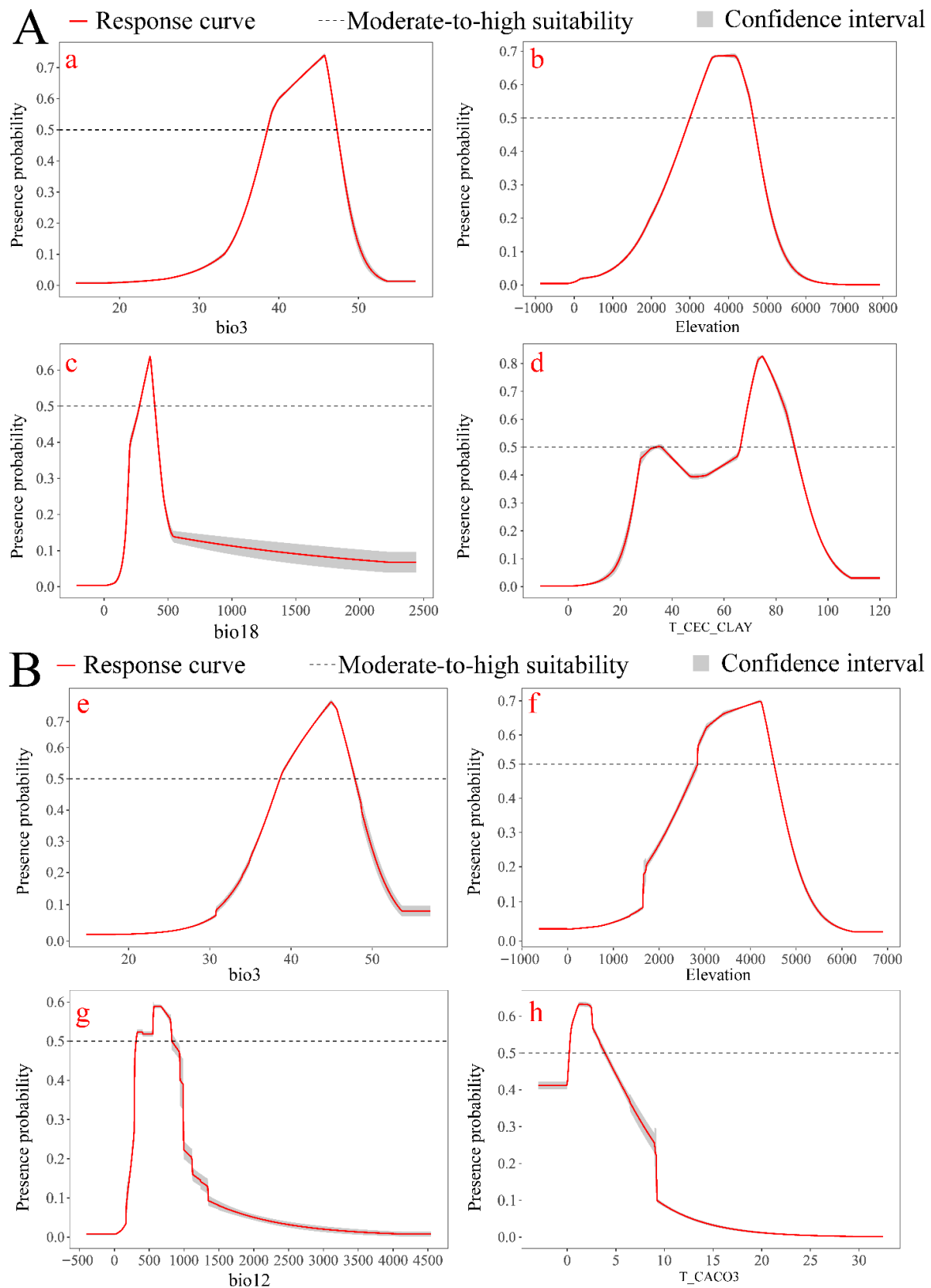


Figure 4. Response curves of the environmental variables used in the MaxEnt models. Panel (A) shows the response curves for the Bangjian population, and Panel (B) shows the response curves for the Jieji population. Subplots (a–d) represent the four variables for Bangjian: (a) bio3 (isothermality); (b) elevation; (c) bio18 (precipitation of the warmest quarter); and (d) T_CEC_CLAY (cation exchange capacity). Subplots (e–h) represent the four variables for Jieji: (e) bio3 (isothermality); (f) elevation; (g) bio12 (annual precipitation); and (h) T_CACO3 (carbonate content).

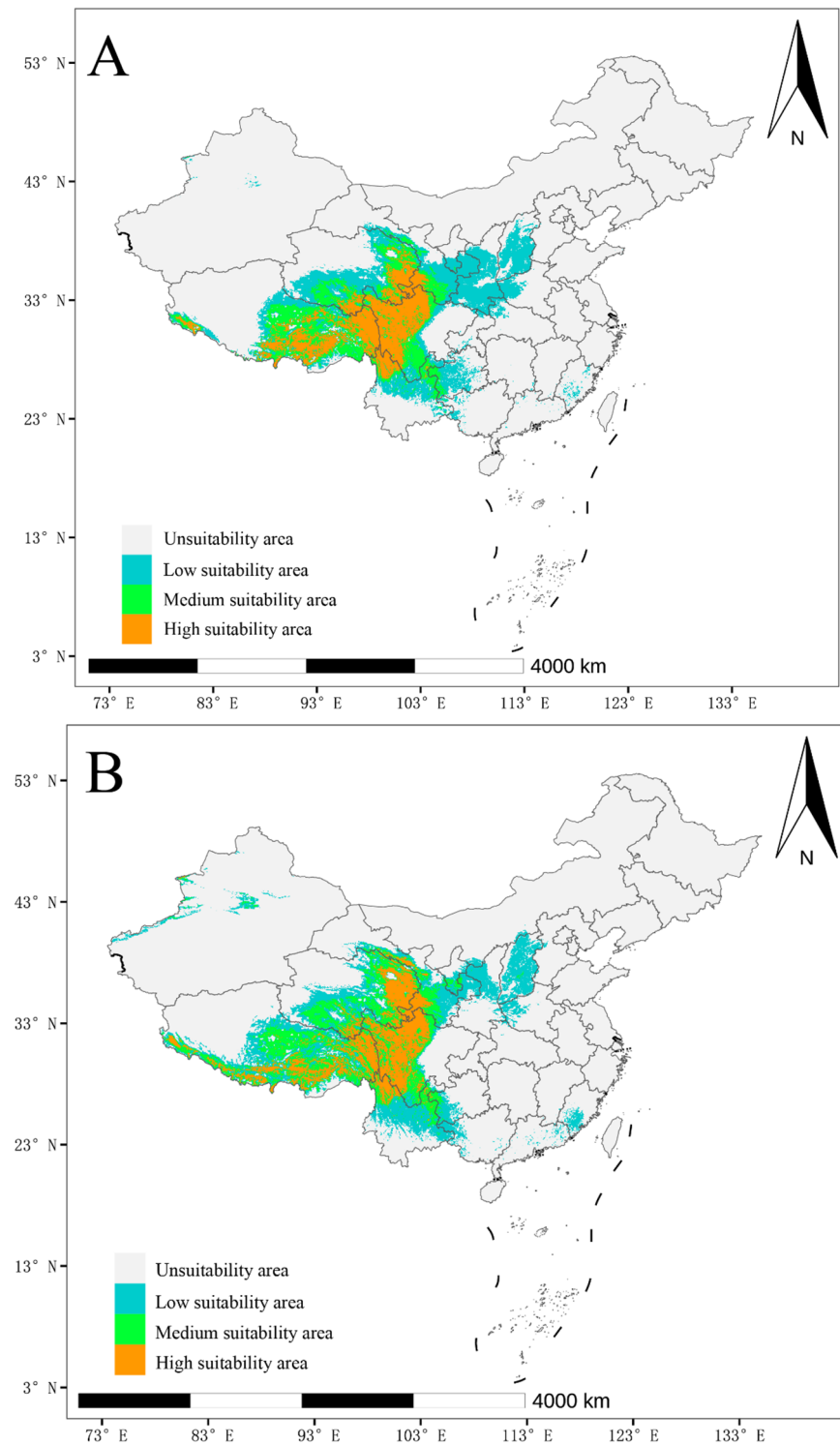


Figure 5. Potential current suitable habitat distribution of Tibetan medicinal *Gentiana*: (A) Bangjian-type *Gentiana* species; (B) Jieji-type *Gentiana* species.

3.4. Dynamic Changes in Suitable Areas Under Different Climate Scenarios

The dynamics of appropriate habitats under future warming scenarios indicated distinct trends for each category (Figure 6, Table 3). Under SSP126, Bangjian-type *Gentiana* demonstrated an initial shrinkage followed by growth, characterized by a net increase of $6.6 \times 10^4 \text{ km}^2$ during 2041–2060. In a contrary pattern, Jieji-type *Gentiana* increased consistently until 2060, peaking at an expansion of $5.44 \times 10^4 \text{ km}^2$ in 2041–2060, before shrinking in the final period (2081–2100).

Table 3. Spatiotemporal Changes in Suitable Habitats for Tibetan Medicinal Species of *Gentiana* Across Periods.

Category	Scenarios	Period	Stable Area (×10 ⁴ km ²)	Expansion Area (×10 ⁴ km ²)	Contraction Area (×10 ⁴ km ²)	Expansion/Contraction (×10 ⁴ km ²)
Bangjian	SSP126	2021–2040	195.7	7	8.73	−1.73
		2041–2060	197.38	13.65	7.05	+6.60
		2061–2080	197.6	9.27	6.84	+2.43
		2081–2100	198.99	11.34	5.45	+5.89
	SSP245	2021–2040	196.09	8.17	8.34	−0.17
		2041–2060	199.05	12.8	5.39	+7.41
		2061–2080	196.66	14.32	7.78	+6.54
		2081–2100	198.46	17.66	5.98	+11.68
	SSP585	2021–2040	196.47	6.72	7.97	−1.25
		2041–2060	194.00	7.4	10.44	−3.04
		2061–2080	195.32	10.63	9.11	+1.52
		2081–2100	189.95	13.1	14.49	−1.39
Jiejí	SSP126	2021–2040	202.9	9.05	8.79	+0.26
		2041–2060	202.15	14.97	9.53	+5.44
		2061–2080	203.65	12.82	8.04	+4.78
		2081–2100	200.02	11.11	11.66	−0.55
	SSP245	2021–2040	197.53	8.06	14.16	−6.10
		2041–2060	200.23	11.16	11.45	−0.29
		2061–2080	197.62	10.81	14.06	−3.25
		2081–2100	199.7	19.74	11.98	+7.76
	SSP585	2021–2040	202.03	12.19	9.66	+2.53
		2041–2060	198.71	9.28	12.97	−3.69
		2061–2080	195.4	13.06	16.29	−3.23
		2081–2100	191.17	14.76	20.51	−5.75

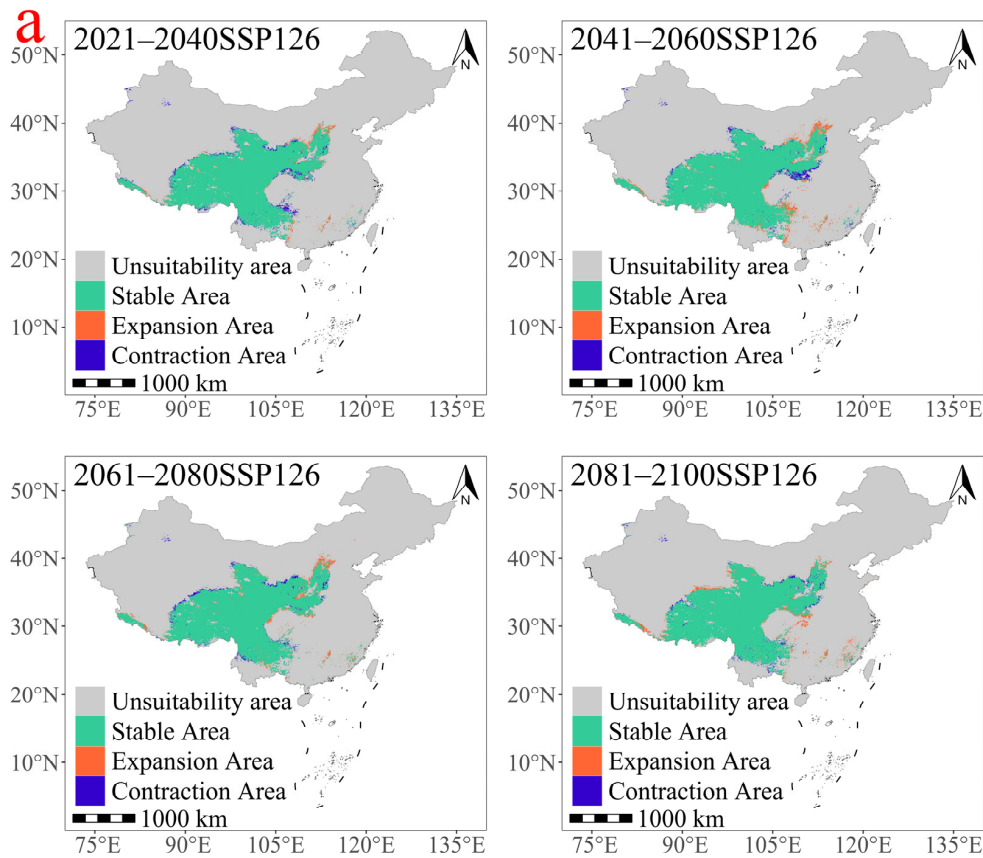


Figure 6. Cont.

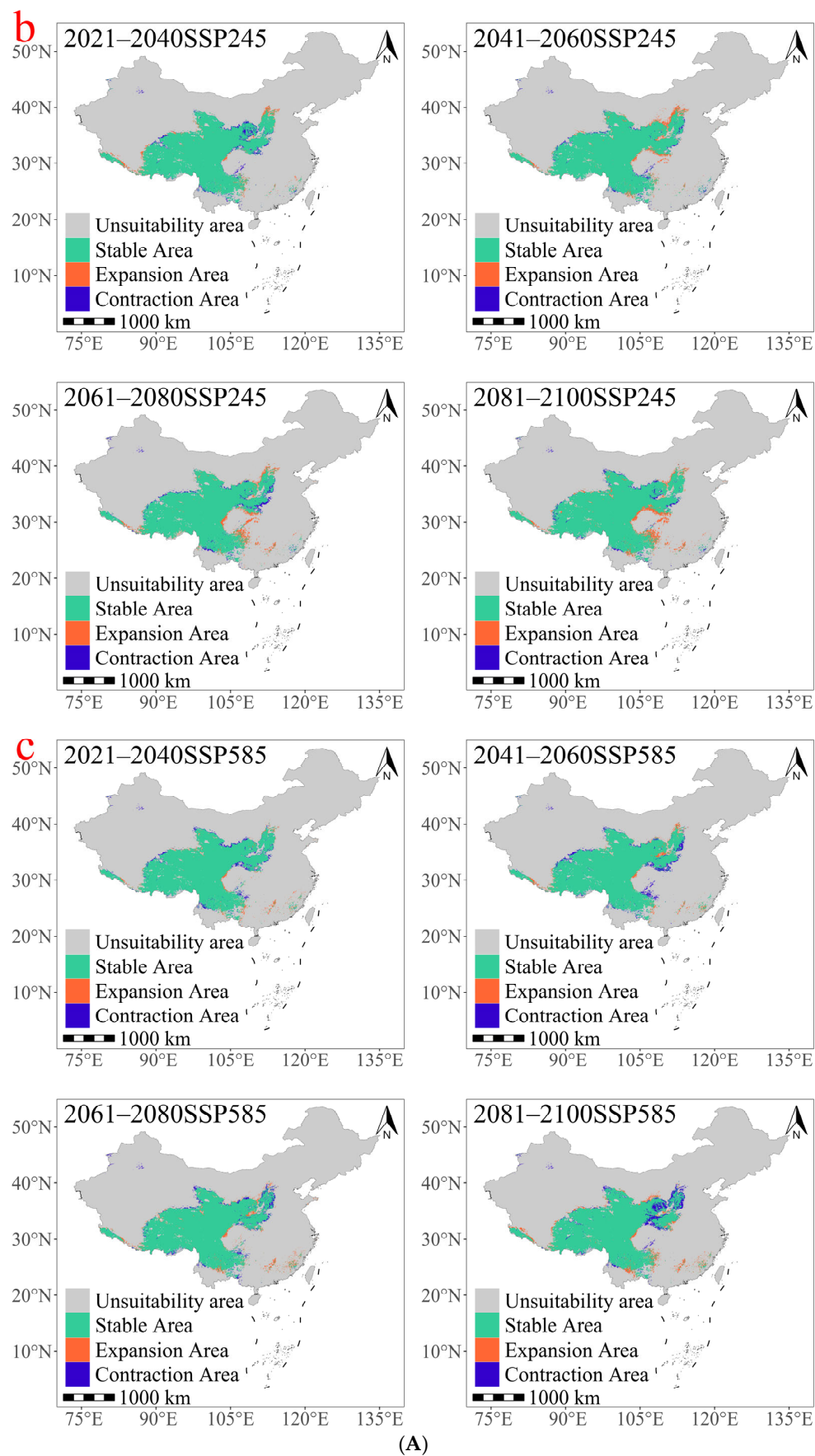


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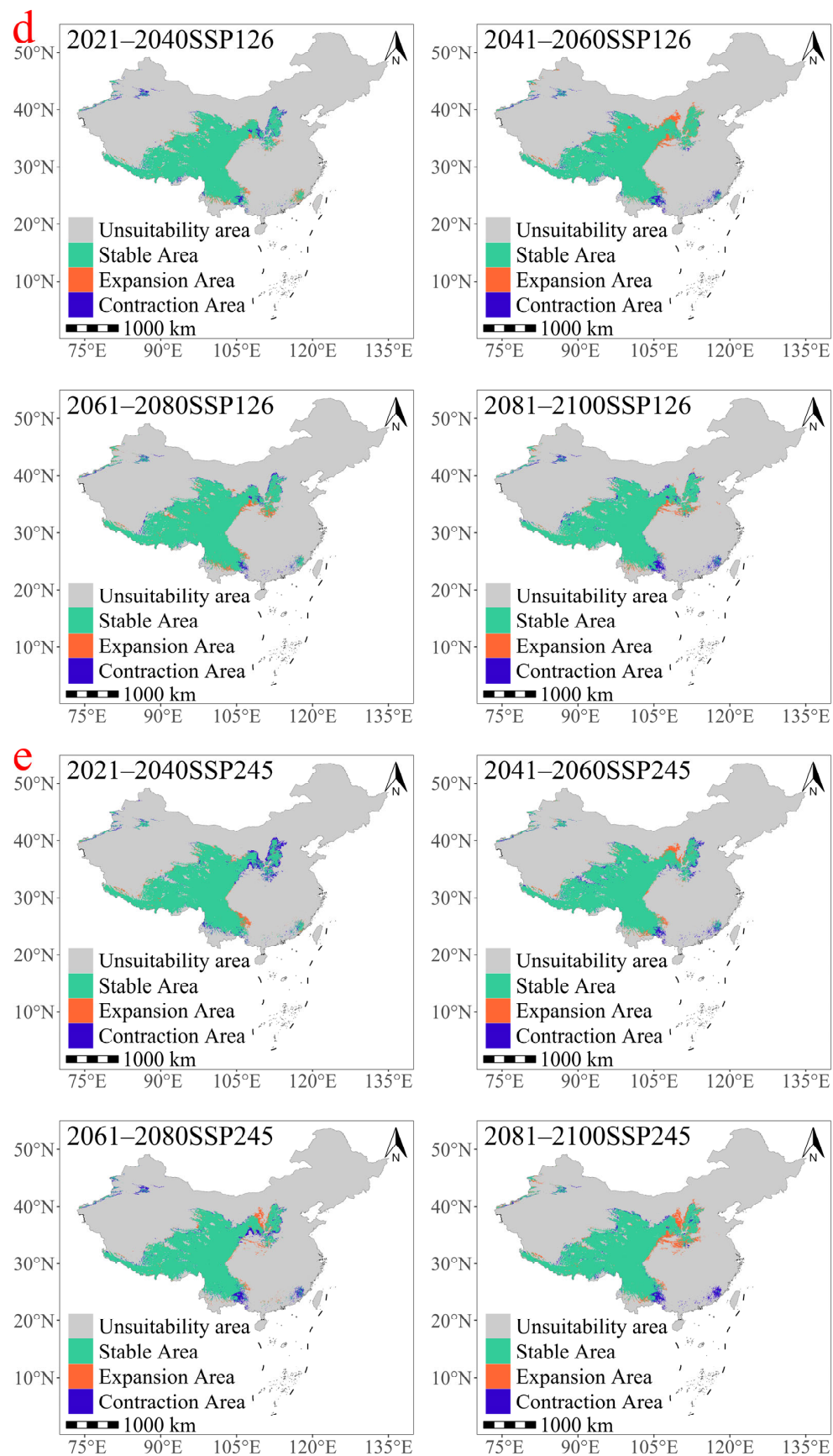


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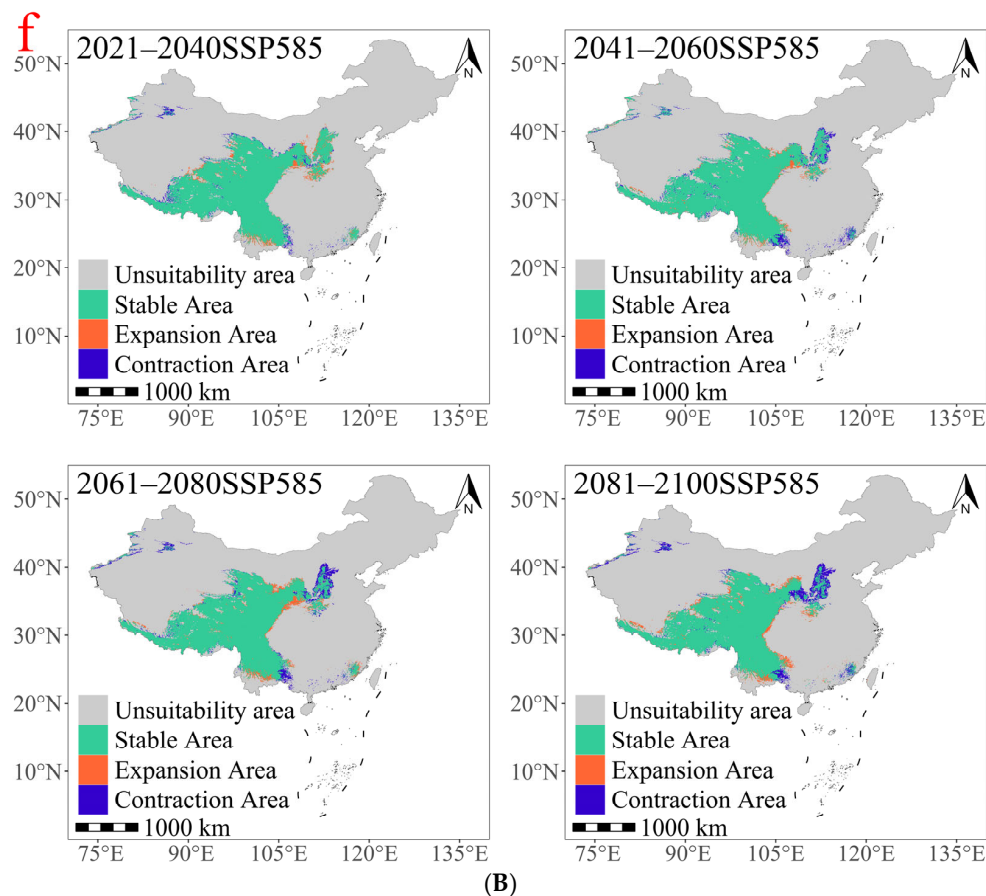


Figure 6. Spatiotemporal dynamics of suitable habitats for Bangjian (A) and Jieji (B) Tibetan medicines across future periods. Subplots (a–c) show Bangjian under SSP126, SSP245, and SSP585 scenarios, respectively; subplots (d–f) show Jieji under SSP126, SSP245, and SSP585 scenarios, respectively. For each subplot, the four time periods correspond to 2021–2040, 2041–2060, 2061–2080, and 2081–2100.

Under SSP245, Bangjian’s pattern followed that under SSP126 but resulted in a more considerable net increase of $11.68 \times 10^4 \text{ km}^2$ during 2081–2100. Jieji, however, experienced a “contraction–expansion” transition, with a net loss of $6.1 \times 10^4 \text{ km}^2$ over 2021–2080 before a late-period increase.

The high-emission SSP585 scenario offered the most severe issues. Bangjian showed a changing “contraction–expansion–contraction” pattern, with a brief expansion phase ($1.52 \times 10^4 \text{ km}^2$) in 2061–2080 amidst general contraction. Jieji fared poorly, increasing only in 2021–2040 ($+2.53 \times 10^4 \text{ km}^2$) and then enduring chronic contraction, which was most severe in 2081–2100 with a loss of $5.75 \times 10^4 \text{ km}^2$.

3.5. Center of Mass Migration

The distribution centroids for both Bangjian and Jieji groups were consistently located in Jiangda County, Changdu City, Xizang, across all assessed climate scenarios and time periods (Figure 7). The current centroids were identified near Boluo Village (98.36893° E , 31.43862° N) for Bangjian and Dedeng Village (97.95395° E , 31.82757° N) for Jieji. Under future climate scenarios, the distribution centroids of both Bangjian and Jieji groups are projected to shift predominantly eastward to southeastward from their current positions (Table 4). Despite this stability, the models indicate a consistent directional trend in centroid migration towards the east-southeast under future climate conditions.

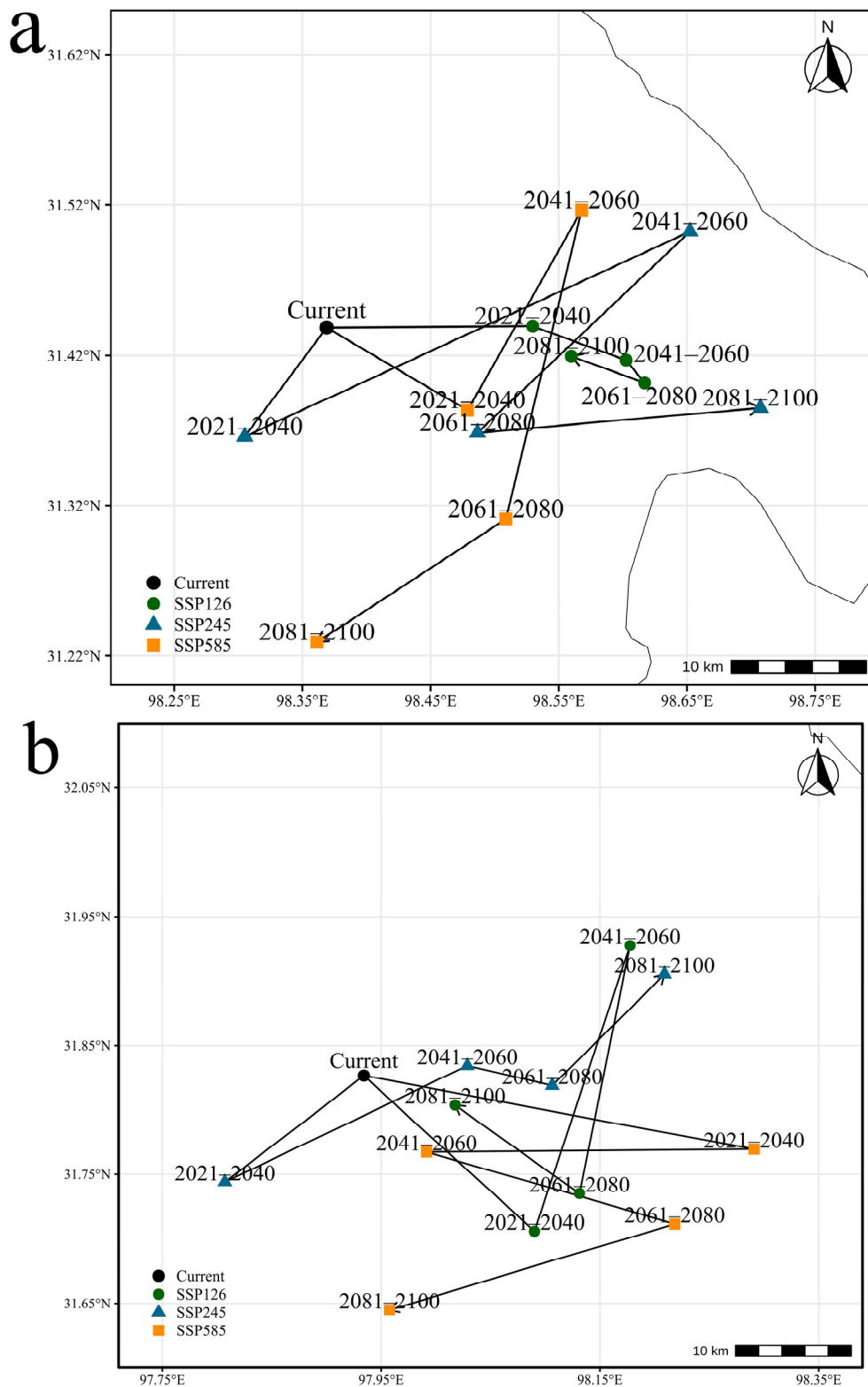


Figure 7. Centroid shifts in suitable habitats across time periods: (a) Bangjian-type species; (b) Jieji-type species.

Table 4. Migration of the Plant Center of *Gentiana* Species in Tibetan Medicine Across Different Periods.

Category	Scenarios	Period	x	y	Distance Traveled (km)	Movement Direction
Bangjian	Current	Current	98.36893	31.43862	NA	NA
	SSP126	2021–2040	98.52969	31.43957	15.28	Southeast
		2041–2060	98.60251	31.41696	7.36	Southeast
		2061–2080	98.61697	31.40196	2.16	Southeast
		2081–2100	98.55979	31.41960	5.78	Northwest
	SSP245	2021–2040	98.30506	31.36603	10.08	Southwest
		2041–2060	98.65236	31.50243	36.32	Northeast
		2061–2080	98.48660	31.36849	21.65	Southwest
		2081–2100	98.70730	31.38498	21.07	Northeast
	SSP585	2021–2040	98.47880	31.38354	12.10	Southeast
		2041–2060	98.56786	31.51658	17.01	Northeast
		2061–2080	98.50874	31.31119	23.46	Southwest
		2081–2100	98.36138	31.22926	16.72	Southwest
Jieji	Current	Current	97.95395	31.82757	NA	NA
	SSP126	2021–2040	98.10669	31.70489	19.86	Southeast
		2041–2060	98.19166	31.92941	26.16	Northeast
		2061–2080	98.14829	31.73734	21.69	Southwest
		2081–2100	98.03728	31.80957	13.22	Northwest
	SSP245	2021–2040	97.82800	31.74566	14.99	Southwest
		2041–2060	98.04208	31.83611	22.62	Northeast
		2061–2080	98.13273	31.82252	8.71	Southeast
		2081–2100	98.22418	31.91097	13.08	Northeast
	SSP585	2021–2040	98.30971	31.77338	34.22	Southeast
		2041–2060	98.01053	31.77206	28.34	West
		2061–2080	98.23209	31.71159	22.04	Southeast
		2081–2100	97.97321	31.64626	25.59	Southwest

4. Discussion

4.1. Model Performance and Factor Analysis

The Maximum Entropy (MaxEnt) model, first established by Jaynes in 1957 [33], uses occurrence records and environmental variables to forecast species' ecological niches. It is still one of the most extensively used species distribution models (SDMs) [34]. In this work, environmental predictors were submitted to a two-stage filtering process: an initial screening using MaxEnt to identify low-contribution variables, followed by Pearson correlation analysis to remove significantly intercorrelated predictors ($|r| > 0.8$). This strategy was implemented to mitigate overfitting and multicollinearity, thus improving model accuracy [35,36]. The ENMeval package in R was used to fine-tune the regularization multiplier (RM) and feature classes (FC) after that. We used Akaike's Information Criterion corrected for small sample sizes (AICc) to determine how well the model fits, and we chose the optimal parameter configuration (lowest AICc) for the final forecast. The area under the receiver operating characteristic curve (AUC) was utilized to further test the model's performance. This is a standard method for assessing model accuracy and preventing overfitting [37,38]. Following optimization, the models for the Bangjian and Jieji groups achieved high AUC values of 0.925 and 0.924, respectively, confirming their strong predictive reliability in identifying suitable habitats for these Tibetan medicinal plants across China.

4.2. Dominant Environmental Drivers

Elevation was the primary factor affecting the distribution of both medicinal *Gentiana* types. It contributed 44.5% and 34% to the models for Bangjian and Jieji, respectively. Prediction results showed that highly suitable areas were mainly in high-altitude regions like Qinghai, Southeastern Xizang, and Western Sichuan. This distribution is comparable with data in the Flora of China [8], with an average altitude exceeding 4000 m [39],

which likely explains why elevation emerged as a dominant driver in our models. Studies by Li Haiming, Li Xiaoli, Sun Chenglin et al. on alpine medicinal plants, including *Stellera chamaejasme* L., *Rhododendron anthopogonoides* Maxim., and *Saussurea medusa* Maxim., likewise revealed elevation as the key factor impacting distribution [40–42], corroborating our findings.

Temperature and moisture were also important factors, besides elevation. Due to China's complex topography, rainfall and temperature vary greatly across different regions [43]. Interestingly, precipitation added more to Bangjian's distribution than temperature, while the opposite was true for Jieji. This may relate to their different habitats: our field surveys found that Bangjian often grows in moist environments like slopes and marshlands, while Jieji usually occurs in forest understory and slopes. Isothermality (bio3) was the most influential temperature variable for both types, providing 12.1% for Bangjian and 30.9% for Jieji. For precipitation, the key factors differed: precipitation of the warmest quarter (bio18) was most important for Bangjian (29.1%), while annual precipitation (bio12) was dominant for Jieji (20.6%). These patterns match the genus's known preference for cool, moist habitats such as meadows, proving its ecological adaptation to "cool-moist" conditions and sensitivity to dry-warm environments [44,45]. Studies of *G. veitchiorum* Hemsl [46] also stressed warm-season precipitation as a key factor, aligning with our results.

Soil factors had the least influence on distribution. Both *Gentiana* types are mainly found on the Qinghai–Tibet Plateau and surrounding areas, where diverse landforms create varied soil types. Our field surveys confirmed that Bangjian and Jieji grow in different soil types, which may explain why soil is not a limiting factor. Similarly, studies on *Ophiocordyceps sinensis* and *Przewalskia tangutica* also reported minimal soil influence on distribution in this region [47,48].

4.3. Climate Change Impacts and Habitat Dynamics

Climate serves as a key driver of species distribution, and its ongoing changes greatly reshape suitable habitat ranges [49,50]. Studies suggest that climate warming may elevate temperatures by over 1.5 °C and increase annual precipitation by more than 10% across much of China [51]. Our findings show that under SSP126 and SSP245 scenarios, Bangjian-type *Gentiana* exhibits long-term expansion of suitable habitats, despite short-term declines. In contrast, Jieji-type *Gentiana* stays most stable under SSP126, showing expansion in three of the four studied periods, except during 2081–2100. Under SSP245 and SSP585 scenarios, however, its habitats usually contract. Under the high-emission SSP585 scenario, both medicinal types experience major habitat loss, shifting from low-elevation areas—such as Shaanxi, Shanxi, and Southeastern Yunnan—toward the Tibetan Plateau. This upward shift is also found in predictions for other alpine plants [52]. Bangjian's expansion under moderate climate situations (SSP126 and SSP245) may stem from its lower sensitivity to temperature compared to Jieji. Field surveys show that Bangjian flowers 1–2 months later and usually grows at higher elevations. Warmer conditions may advance its flowering time, potentially facilitating habitat expansion [53,54]. Under the extreme SSP585 situation, however, both species retreat to higher altitudes. Intensive warming raises temperatures, increases glacial meltwater, and improves precipitation in high-elevation zones, creating more favorable conditions for alpine plants. In contrast, warming and humidity changes in low-elevation areas likely exceed the ecological limits of these two *Gentiana* species [2,55,56]. These projected shifts stress the urgency of building region-specific conservation strategies to safeguard these Tibetan medicinal plants and their habitats under ongoing climate change.

4.4. Limitations and Future Research

This study provides projections of potentially suitable habitats for two major types of Tibetan medicinal *Gentiana* using 12 environmental variables, yet several limitations should be recognized. (1) Exclusion of manmade factors: Human impact was not incorporated into the model. Specific data on herb-gathering by local communities were lacking, preventing its inclusion in the projections. While human activities such as tourism, grazing, and industrialization greatly impact alpine plants through soil alteration and local climate disruption [57], available human footprint data are limited to 2000–2020. Moreover, human activity indices often aggregate diverse pressures into a single metric, which may mask sector-specific effects [58]. Future studies should integrate more thorough and prospective human activity data. (2) Model constraints: The MaxEnt model simplifies species–environment links by evaluating variables individually, thus failing to fully capture complex interactions among environmental factors [59]. Furthermore, as model performance is highly dependent on data quality, this study primarily utilized readily available and reliable datasets for analysis. (3) Taxonomic and genetic resolution: Although this study classified species according to traditional Tibetan medicinal categories—which suitably reflects local resource use patterns—the analysis was hampered by limited genetic diversity studies and small sample sizes for some species. This stopped species-level modeling aligned with modern taxonomy. Future work should combine more comprehensive genetic and occurrence data to assess distribution patterns at finer taxonomic resolutions.

4.5. Conservation Implications

Conservation strategies for Bangjian-type and Jieji-type *Gentiana* should account for their specific ecological traits and adaptive capacities. For the more ecologically tolerant Bangjian group, focus should be given to protecting habitat integrity and sustaining ecosystem stability. For the more vulnerable Jieji group—particularly endangered species such as *G. thassica* Burkill (CR) and *G. waltonii* Burkill (VU), which show significant habitat contraction and low reproductive capacity—enhanced artificial propagation, germplasm conservation, and ex situ protection are recommended to strengthen population resilience. Areas anticipated to remain constant or expand under future climatic scenarios should be identified as priority conservation zones, functioning as possible climate refugia. Additionally, building a climate-informed dynamic habitat monitoring and early-warning system, linked into regional biodiversity management plans, would enable prompt strategy revisions and improve adaptive management. The complementary application of in situ preservation and assisted propagation measures will ensure the long-term conservation and sustainable exploitation of these unique Tibetan medicinal plant resources.

5. Conclusions

- (1) Utilizing the Maximum Entropy (MaxEnt) model with twelve selected environmental factors, this study found that altitude, temperature, and precipitation are the primary dominant factors determining the distribution of the Tibetan medicinal herbs Bangjian and Jieji.
- (2) Under current climatic conditions, the total suitable habitat for Bangjian and Jieji was estimated to be $208.86 \times 10^4 \text{ km}^2$ and $211.70 \times 10^4 \text{ km}^2$, respectively. The highly suitable areas for both are primarily concentrated in the southeastern part of the Qinghai–Tibet Plateau.
- (3) Under future climate scenarios, the suitable habitat for Jieji is projected to contract, showing a moderate expansion trend towards Central China only under the SSP126 scenario. In contrast, the suitable habitat for Bangjian is generally expected to expand,

except under the SSP585 scenario. The centroid of suitable habitats for both types is projected to shift eastward.

- (4) Based on future climate projections, Jieji-class Tibetan medicines exhibit higher climate sensitivity compared to Bangjian-class varieties, warranting prioritized conservation measures such as the establishment of seed banks and nature reserves.
- (5) These findings establish a scientific basis for understanding the potential impacts of climate change on the distribution of Gentiana-based Tibetan medicinal resources and offer critical insights to inform ecological conservation strategies and future research.
- (6) Future research should aim to integrate anthropogenic factors and develop species-specific distribution models for individual medicinal plants.

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