Prediction of Distribution Patterns and Dominant Climatic Factors of Cymbidium in China Based on the MaxEnt Model (Postprint)

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Abstract

All species of the genus Cymbidium (except C. lancifolium) are listed as nationally key protected wild plants. Investigating their potential distribution patterns under future climate conditions will provide references and basis for effective and rational protection of this group. Based on known distribution points of Cymbidium plants and 19 climatic factors, this study employs the MaxEnt model and Geographic Information System (ArcGIS) to simulate the potential distribution patterns of the genus Cymbidium and 20 species thereof under nine different climate scenarios (contemporary and four future time periods: 2030s, 2050s, 2070s, and 2090s, each with two greenhouse gas emission scenarios), and to identify the dominant climatic factors influencing the distribution of Cymbidium plants. The results indicate that: (1) Precipitation of the driest quarter (Bio17), annual precipitation (Bio12), and temperature seasonality (Bio04) are the dominant climatic factors influencing the geographical distribution patterns of Cymbidium plants; (2) At the species level, different Cymbidium species exhibit different changing trends in suitable habitat areas under future scenarios, and the dominant climatic factors affecting their distribution also vary. Among them, eight species such as Cymbidium dayanum show an overall expansion trend in suitable habitat area, while twelve species such as Cymbidium tracyanum show an overall contraction trend in suitable habitat area. This study will provide important references for in situ and ex situ conservation of Cymbidium plants, and holds positive significance for the conservation of endangered wild plants such as Cymbidium.

Predicting the Distribution Patterns and Dominant Climatic Factors of Cymbidium in China Using the MaxEnt Model

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Abstract

All species of the genus *Cymbidium* (except *C. lancifolium*) are listed as nationally key protected wild plants in China. Investigating their potential distribution patterns under future climate conditions will provide essential references and a scientific basis for the effective and rational conservation of this group. Based on known distribution points of *Cymbidium* species and 19 climatic factors, this study employed the MaxEnt model and Geographic Information System (ArcGIS) to simulate the potential distribution patterns of the genus *Cymbidium* and 20 of its constituent species under nine different climate scenarios (contemporary conditions and two greenhouse gas emission pathways for the 2030s, 2050s, 2070s, and 2090s). The dominant climatic factors influencing the distribution of *Cymbidium* were identified. The results indicate: (1) Precipitation of the driest quarter (Bio17), annual precipitation (Bio12), and temperature seasonality (Bio04) are the dominant climatic factors shaping the geographic distribution patterns of *Cymbidium*. (2) At the species level, different *Cymbidium* species exhibit divergent trends in suitable habitat area under future scenarios, with varying dominant climatic factors influencing their distributions. Specifically, eight species including *C. dayanum* show an overall expansion trend in suitable habitat area, while 12 species including *C. tracyanum* demonstrate a contraction trend. This study provides important references for both in-situ and ex-situ conservation of *Cymbidium* species and holds positive significance for the protection of endangered wild plants such as *Cymbidium*.

Keywords: MaxEnt model, species distribution models, dominant climate factor, conservation strategy, climate change

Introduction

Climate is one of the most critical factors influencing species' natural geographic distributions, and climate change affects ecosystem structure and function, community composition, species distribution patterns, and biodiversity (Robert &

Raza, 2010; Bellard et al., 2012; Veloz et al., 2012; Shen & Wang, 2013). Over the past century, human activities have caused global average surface temperatures to rise by approximately 0.85°C, with projections indicating a further increase of 0.3–4.8°C by the end of the 21st century compared to baseline periods, accompanied by significant changes in precipitation patterns (IPCC, 2014; Qin et al., 2007). Global climate change may lead to the expansion or contraction of most species' ranges, with habitat loss and fragmentation potentially causing extinction of endangered species with narrow natural distributions (Root et al., 2003; Thomas et al., 2004; Chen et al., 2011; Zhou et al., 2016). Consequently, global climate change will impact the geographic distribution patterns of plants (Bertin, 2008).

Species Distribution Models (SDMs) (Elith & Leathwick, 2009) demonstrate strong predictive capability for changes in species' potential distribution areas under different climate scenarios and have been widely applied to plants (Sunil & Thomas, 2009; Adhikari et al., 2012; Hu et al., 2015; Zhang et al., 2019) and animals (Yang et al., 2020). Among these, the Maximum Entropy (MaxEnt) ecological niche model, developed by Phillips et al. (2006), offers accurate predictions and robust performance (Xu et al., 2015) and has become the most widely used approach, with applications in *Uraria* (Zhu et al., 2020), *Cymbidium goeringii* and *C. faberi* (Liang et al., 2018), *Acer catalpifolium* (Huang et al., 2021), and *Tsuga longibracteata* (Tan et al., 2018).

The genus *Cymbidium* represents one of the most horticulturally valuable groups in the Orchidaceae family, long favored by scholars and the public for its significant scientific, economic, cultural, and social value. The genus comprises approximately 80 species worldwide (Hunt, 1970; Long et al., 2003; Yang et al., 2013; Liu et al., 2006), primarily distributed across tropical and subtropical regions of Asia and northern Australia, typically inhabiting cool, high-altitude areas (Chen, 1999). These orchids commonly grow in humus soil under forest canopies, occasionally on rocks or as epiphytes on tree trunks. China serves as a diversity center for this genus, hosting approximately 60 species, with over 20 being endemic to the country (Liu & Zhang, 1998; Liu & Chen, 2002; Liu & Chen, 2004; Liu et al., 2005). However, due to intensifying climate change and human disturbance in recent years, suitable habitats for orchids have deteriorated dramatically, with wild resources declining progressively and most orchid species facing severe survival threats, classified as threatened in the *China Species Red List*.

This study focuses on *Cymbidium* species, selecting 19 climatic factors as environmental variables. Based on location information obtained from germplasm resource surveys and literature review, as well as distribution data collected from the Chinese Virtual Herbarium (https://www.cvh.ac.cn/), we employed the MaxEnt model and ArcGIS spatial analysis technology to simulate and predict the potential distribution areas of this genus under different scenarios. The study addresses the following questions: (1) predicting and analyzing potential distribution pattern changes of *Cymbidium* under different future climate scenarios; (2) identifying the dominant climatic factors influencing the distribution patterns of *Cymbidium*; and (3) providing theoretical foundations and practical references for field surveys, systematic taxonomy, biogeography, and conservation biology research on *Cymbidium*.

1.1.1 Germplasm Resources Survey

Based on distribution and trait descriptions documented in *Flora of China* (Chen, 1999), literature, and herbarium records, we examined historical distribution points of *Cymbidium* species. Field surveys were conducted across actual distribution areas within China, recording information for each population including location, latitude and longitude, elevation, threat factors, and habitat type.

1.1.2 Species Distribution Information

Species distribution data were obtained from three sources: (1) germplasm resource surveys by our research team, with latitude and longitude coordinates acquired through GPS positioning in the field; (2) published literature from domestic and international sources, from which reported distribution locations were identified and corresponding coordinates obtained using Baidu coordinate extraction tools; and (3) herbarium specimen collection locality data from the Chinese Virtual Herbarium (http://www.cvh.ac.cn/) and the Global Biodiversity Information Facility (https://www.gbif.org/). Through these three approaches, we compiled 3,170 distribution records for 35 *Cymbidium* species in China. After removing cultivation and purchase sites, as well as overlapping and ambiguous records, we obtained 915 valid distribution records for 24 species.

1.1.3 Climate Factor Data

This study selected 19 climatic factors for modern (1970–2000) and future periods (2030s: 2021–2041; 2050s: 2041–2060; 2070s: 2061–2080; 2090s: 2081–2100), all sourced from the WorldClim database (http://worldclim.org) at 2.5 spatial resolution. Modern climate data were generated through interpolation of climate records from global meteorological stations during 1970–2000. Future climate data were selected from the BCC-CSM2-MR model under CMIP6 at 2.5-minute resolution, using two SSP scenarios (SSP1-2.6 and SSP5-8.5). Data were clipped to China's extent and converted to ASCII format using ArcGIS 10.6 software.

1.1.4 Chloroplast Genome Data

A total of 17 published chloroplast genomes of *Cymbidium* species were retrieved from NCBI (https://www.ncbi.nlm.nih.gov/), with the chloroplast genome of

Geodorum eulophioides downloaded as an outgroup. Chloroplast genome information and GenBank accession numbers are detailed in Table 1 . Additionally, chloroplast genomes of *C. cyperifolium*, *C. elegans*, and *C. iridioides* were obtained through sampling and sequencing.

1.2.1 Model Construction

We used MaxEnt version 3.4.1 (http://biodiversityinformatics.amnh.org/open_{source}/maxent) to simulate potential distribution patterns of *Cymbidium* under different climate scenarios, with training and test sets configured at 75% and 25%, respectively. Species distribution data and climate factor data were imported into MaxEnt, with jackknife analysis selected to plot response curves and generate prediction maps.

1.2.2 Model Accuracy Assessment

Model accuracy was evaluated using Receiver Operator Characteristic (ROC) curves. The area under the ROC curve (AUC) is independent of threshold values and can be used to assess prediction model accuracy (Guo et al., 2017; Deng et al., 2014; Zhou et al., 2019). AUC values range from 0 to 1, with higher values indicating greater deviation from random distribution and better predictive performance. AUC values of 0.5–0.6 indicate prediction failure; 0.6–0.7 represent poor performance; 0.7–0.8 indicate fair performance; 0.8–0.9 represent good performance; and 0.9–1.0 indicate excellent performance.

1.2.3 Suitable Habitat Classification

MaxEnt output files in ASCII format were loaded into ArcGIS 10.6, converted to raster data using the "Conversion Tools" in ArcToolbox, and reclassified into four habitat suitability categories (unsuitable, low suitability, moderate suitability, and high suitability) using the "Reclassify" tool with the natural breaks classification method. Areas of each suitability class were then calculated.

1.2.4 Phylogenetic Tree Construction

Using *Geodorum eulophioides* as the outgroup, whole chloroplast genome sequences of 20 *Cymbidium* species were aligned using HomBlocks software (Bi et al., 2017). The aligned sequences were used to construct a Maximum Likelihood (ML) phylogenetic tree using IQ-TREE version 2.1.2 (Trifinopoulos et al., 2016), with bootstrap values set to 1,000 and the optimal model selected by the built-in ModelFinder (Kalyaanamoorthy et al., 2017).

2.1.1 Model Accuracy Assessment

The MaxEnt model constructed based on 19 climatic factors for the entire *Cymbidium* genus and 20 individual species (the remaining four species had insufficient location data for reliable individual predictions and were used only for genus-level distribution modeling) yielded AUC values ranging from 0.849 to 0.992 across contemporary and future climate scenarios (Table 2), with a mean value of 0.953.

ROC curve analysis of MaxEnt predictions for the entire genus under current climate conditions revealed training and test AUC values of 0.916 and 0.911, respectively, substantially exceeding the random prediction value of 0.5 (Figure 1 [Figure 1: see original paper]). These results demonstrate high model accuracy, validating its use for simulating potential distribution areas of *Cymbidium* in China.

2.1.2 Dominant Climatic Factors Influencing *Cymbidium* Distribution

Contribution percentages of climatic factors to the species distribution model (Table 3) show that under current climate scenarios, the most influential factors for the genus-level geographic distribution are precipitation of the driest quarter (Bio17), annual precipitation (Bio12), and temperature seasonality (Bio04), with contribution rates of 46.3%, 28.4%, and 7.2%, respectively, summing to 81.9%.

To avoid autocorrelation among climatic factors, we extracted climate factor information for 915 *Cymbidium* distribution points using ArcGIS 10.6 and analyzed correlations using Pearson correlation coefficients in SPSS 23.0. Factors with correlation coefficients $|r| < 0.8$ were retained; for $|r| > 0.8$, the factor with higher contribution rate was retained. This screening yielded seven climatic factors: Bio2, Bio4, Bio6, Bio10, Bio12, Bio17, and Bio18. Analysis using these filtered factors confirmed that precipitation of the driest quarter (Bio17), annual precipitation (Bio12), and temperature seasonality (Bio04) remained the dominant factors, with contribution rates of 50.0%, 27.3%, and 15.9%, respectively, totaling 93.2%. Jackknife tests (Figure 2 [Figure 2: see original paper]) indicated that annual precipitation (Bio12) showed the highest test gain when used alone, while temperature seasonality (Bio04) caused the greatest decrease in gain when omitted.

Response curves of *Cymbidium* distribution to these three key factors are shown in Figure 3 [Figure 3: see original paper]. The genus has highest probability of occurrence in areas with 50–200 mm precipitation in the driest quarter, with a positive correlation up to 57 mm, beyond which the correlation becomes negative. Distribution probability becomes unaffected when precipitation exceeds 630 mm. Maximum occurrence probability occurs at 2,000 mm annual precipitation, with a negative correlation beyond this threshold, stabilizing when annual precipitation reaches 4,000 mm. Temperature seasonality shows peak occurrence probability at approximately 3°C, with probability declining sharply as seasonality increases.

At the species level, dominant climatic factors vary: temperature seasonality (Bio04) and mean temperature of the coldest quarter (Bio11) for *C. dayanum* and *C. eburneum*; annual temperature range (Bio07) and temperature seasonality (Bio04) for *C. serratum*; precipitation of the wettest quarter (Bio16) and driest quarter (Bio17) for *C. sinense* and *C. aloifolium*; isothermality (Bio03) and temperature seasonality (Bio04) for *C. lowianum* and *C. iridioides*; isothermality (Bio03), temperature seasonality (Bio04), and minimum temperature of the coldest month (Bio06) for *C. erythraeum* and *C. elegans*; annual precipitation (Bio12) and precipitation of the driest quarter (Bio17) for *C. kanran*, *C. ensifolium*, and *C. floribludum*; minimum temperature of the coldest month (Bio06) and annual temperature range (Bio07) for *C. macrorhizon*; precipitation of the driest quarter (Bio17) and precipitation of the warmest quarter (Bio18) for *C. lancifolium*; isothermality (Bio03), temperature seasonality (Bio04), precipitation of the driest quarter (Bio17), and precipitation of the warmest quarter (Bio18) for *C. tracyanum*; annual temperature range (Bio07) and precipitation of the driest quarter (Bio17) for *C. cyperifolium*; temperature seasonality (Bio04) and precipitation of the warmest quarter (Bio18) for *C. hookerianum*; mean temperature of the coldest quarter (Bio11) for *C. mannii*; annual precipitation (Bio12) and precipitation of the driest month (Bio14) for *C. goeringii*; and minimum temperature of the coldest month (Bio06), annual precipitation (Bio12), and precipitation of the driest quarter (Bio17) for *C. faberi*.

2.1.3 Potential Geographic Distribution Patterns of *Cymbidium* Under Modern and Future Climate Scenarios

Using modern climate scenarios and two representative concentration pathways (SSP1-2.6 and SSP5-8.5) for the 2030s, 2050s, 2070s, and 2090s, we simulated potential distribution patterns of *Cymbidium* using the MaxEnt model, obtaining suitable habitat areas under different climate scenarios (Appendix 1, Figure 4 [Figure 4: see original paper], Figures 6 [Figure 6: see original paper]–9 [Figure 9: see original paper]).

Under modern climate conditions, the total suitable area for *Cymbidium* is 248.18×10^4 km^2, comprising 100.37×10^4 km^2 of high-suitability area, 80.43×10^4 km^2 of moderate-suitability area, and 67.39×10^4 km^2 of low-suitability area (Appendix 1, Figure 4 [Figure 4: see original paper]). Change curves for suitable habitat area under different future greenhouse gas emission scenarios (Figure 5 [Figure 5: see original paper]) reveal a contracting trend in total suitable area, with high-suitability area showing the greatest reduction (up to 33.08%), moderate-suitability area decreasing by up to 15.57%, while low-suitability area exhibits an increasing trend.

At the species level, *C. dayanum*, *C. macrorhizon*, *C. sinense*, *C. serratum*, *C. lowianum*, *C. lancifolium*, *C. aloifolium*, and *C. eburneum* show overall expansion trends in suitable habitat area compared to modern climate conditions across eight future scenarios. Notably, *C. eburneum* and *C. lancifolium* exhibit decreasing low-suitability areas but substantial increases in high- and moderate-suitability areas. *C. dayanum* and *C. serratum* show substantial increases in total, high, moderate, and low-suitability areas across all four future periods under SSP1-2.6, with high-suitability area also increasing substantially under

SSP5-8.5 (Figure 4 [Figure 4: see original paper]). *C. lowianum* shows substantial increases in total, high, moderate, and low-suitability areas across all four future periods under SSP5-8.5, while under SSP1-2.6, total, moderate, and low-suitability areas expand (except for high-suitability area). In the 2090s, *C. aloifolium* shows increased total, high, moderate, and low-suitability areas under both scenarios. *C. sinense* and *C. macrorhizon* exhibit substantial increases in total, high, and low-suitability areas under both SSP1-2.6 and SSP5-8.5, with moderate-suitability area also showing an overall increasing trend. Specifically, *C. sinense* shows a 68.42% increase in high-suitability area in the 2090s under SSP5-8.5.

Conversely, *C. tracyanum*, *C. hookerianum*, *C. erythraeum*, *C. elegans*, *C. mannii*, *C. cyperifolium*, *C. floribludum*, *C. kanran*, *C. faberi*, *C. goeringii*, *C. iridioides*, and *C. ensifolium* show overall contraction trends in suitable habitat area under future scenarios. Specifically, *C. erythraeum* and *C. elegans* exhibit decreasing total, high, moderate, and low-suitability areas across all four future periods under both scenarios, with reductions ranging from 3.05% to 58.88%. *C. elegans* and *C. mannii* show increased high-suitability area under SSP5-8.5 (2061–2100) but decreased total, moderate, and low-suitability areas under other scenarios. *C. floribludum* shows contracting total and high-suitability areas across eight future scenarios, with minimal changes in moderate and low-suitability areas. *C. cyperifolium* exhibits decreased total, high, moderate, and low-suitability areas under SSP1-2.6 (2041–2080) and SSP5-8.5 (2081–2100). *C. tracyanum* and *C. hookerianum* show significantly reduced total and high-suitability areas under SSP5-8.5 (2061–2100). *C. kanran* shows a contracting high-suitability area. *C. faberi* exhibits decreasing total and moderate-suitability areas. *C. goeringii* shows contracting total suitable area under both scenarios across all periods, particularly in high- and moderate-suitability areas. *C. iridioides* and *C. ensifolium* show slightly contracting total suitable areas, with high- and moderate-suitability areas fluctuating substantially across future periods. By the 2090s, *C. iridioides* shows decreased high-suitability but increased moderate-suitability area under SSP1-2.6, while under SSP5-8.5, high-suitability area increases and moderate-suitability area decreases.

Phylogenetic Relationships of 20 *Cymbidium* Species

Based on whole chloroplast genome sequences and using *Geodorum eulophioides* as the outgroup, we constructed a phylogenetic tree for 20 *Cymbidium* species (Figure 10 [Figure 10: see original paper]). Bootstrap values for most branches in the constructed tree are 100%, indicating high reliability of the phylogenetic relationships based on chloroplast genome sequences. The phylogenetic tree clearly shows that *Cymbidium* species cluster into three major clades: C1, C2, and C3. The C1 clade includes species with terrestrial, terrestrial or epiphytic, and holomycotrophic lifestyles, while species in the C2 and C3 clades are all epiphytic. A heatmap displays changes in the sum of high- and moderate-suitability areas for each species under SSP1-2.6 and SSP5-8.5 scenarios by 2100, revealing both expanding and contracting species within each major and minor clade.

Discussion

A species' distribution range represents a crucial spatial characteristic closely related to extinction risk, ecological invasion, and niche breadth, holding significant importance for studying species origin, dispersal, and evolution. Under the backdrop of global change, simulating potential distribution areas and analyzing dominant factors can provide scientific foundations for effective conservation and sustainable utilization of plant resources. For numerous extant rare and endangered species, potential contraction or expansion trends in distribution ranges carry particularly critical conservation implications.

This study employed the Maximum Entropy model to simulate potential distribution patterns of *Cymbidium* under modern and future climate scenarios (SSP1-2.6, SSP5-8.5). The results indicate that at the genus level, *Cymbidium*'s potential distribution area shows a contracting trend under future climate change, with high-suitability area decreasing substantially by 9.26%–33.08% across eight scenarios. Moderate-suitability area contracts by 7.57% and 7.77% by 2100 under both scenarios, while low-suitability area shows an expansion trend, increasing by 1.68%–20.15% across different scenarios and periods. The dominant climatic factors influencing *Cymbidium* distribution are precipitation of the driest quarter (46.3%), annual precipitation (28.4%), and temperature seasonality (Bio04).

As global temperatures rise, the frequency of extreme precipitation events in China intensifies, with SSP5-8.5 showing greater increases in precipitation intensity compared to lower emission scenarios, particularly pronounced in southwestern China (Chen et al., 2015). This suggests that the genus *Cymbidium* as a whole is maladapted to extreme precipitation under future climate scenarios. However, this study encompasses 20 *Cymbidium* species with substantially different life habits, resulting in varied spatial pattern changes among species.

C. dayanum's modern potential suitable area extends beyond its actual current wild distribution in Guangdong, Guangxi, Hainan, Taiwan, and southern Yunnan to include southern Tibet, while southern Fujian, though widely inhabited, contains only small low-suitability areas. Under future climate scenarios, high-suitability areas show expansion trends, becoming more concentrated and continuous, primarily expanding toward higher latitudes, with notable expansion in southern Tibet and Taiwan. This likely reflects climate change-induced increases in high-suitability area. Under future global warming scenarios, China's annual mean temperature is projected to increase by 1.6–5.0°C, with annual precipitation increasing by 1.5–2.0% (Li et al., 2016). Since temperature seasonality (Bio04) and mean temperature of the coldest quarter (Bio11) are the main factors influencing *C. dayanum* distribution, warming conditions will likely drive northward expansion of its high-suitability areas.

C. erythraeum and *C. elegans* show modern potential suitable areas that, in addition to matching existing records in southeastern Tibet, Yunnan, southwestern Sichuan, and central to southwestern Guizhou, also extensively cover coastal areas of Guangdong and Guangxi, as well as Taiwan. Climate factor contribution analysis indicates that isothermality (Bio03), temperature seasonality (Bio04), and minimum temperature of the coldest month (Bio06) are the primary factors influencing these species, with combined contributions of 92.1% and 87.1%, respectively. Under future climate conditions, their suitable areas show contracting trends, shifting overall toward higher elevation regions in Yunnan and southeastern Tibet. This may relate to changing climate zones in Yunnan, where Cheng et al. (2009) demonstrated that tropical zone area has increased while north subtropical and temperate zones have decreased, with climate zones shifting northward but more significantly expanding toward higher elevations.

C. goeringii shows contracting total suitable area across all eight future scenarios. High-suitability area initially increases then decreases under both emission scenarios across different future periods, likely reflecting temperature and precipitation changes under different scenarios. Under SSP1-2.6, high- and moderate-suitability areas expand during 2061–2080 while low-suitability area contracts, but during 2081–2100, high-suitability area contracts by 10.4%, shifting to moderate- and low-suitability areas. Under SSP5-8.5, high-suitability area expands by 5.94% during 2061–2080 while moderate- and low-suitability areas contract, but during 2081–2100, high- and moderate-suitability areas contract by 11.27% and 18.03%, respectively, while low-suitability area expands by 4.54%. These patterns indicate increasingly unsuitable conditions for *C. goeringii* growth and reproduction with rising CO_2 emissions.

Integrating phylogenetic analysis reveals no clear correlation between distribution area change trends and phylogenetic relationships. Closely related species show divergent distribution trends under future scenarios, consistent with ecological niche theory that closely related species with similar life habits do not compete for identical living spaces. Overall, species in the C1 clade are predominantly terrestrial with higher chloroplast genome GC content and mostly show expanding distribution trends, while C2 clade species are epiphytic with lower GC content and predominantly show contracting distribution trends. Under global warming, increasing drought and extreme rainfall will profoundly affect forest distributions (Shi, 2011), consequently impacting epiphytic *Cymbidium* species.

Compared to modern climate, *Cymbidium* at the genus level shows contracting trends under future scenarios, but species-level responses vary, with different species exhibiting distinct distribution pattern changes in response to climate change. Since actual distribution patterns are influenced by multiple factors, future research should incorporate topography, soil conditions, elevation, and human activities.

Why do different species show different distribution trends under identical climate change scenarios? Clearly, this stems from species' existing geographic distribution patterns. However, how do these existing patterns relate to species' biological and ecological characteristics—which species will contract or expand? This represents a core concern in evaluating climate change impacts on species distributions. Most scholars believe that under global warming, species' suitable areas will continuously decrease and shift toward higher latitudes and elevations (Parmesan, 2006). For example, Qiu et al. (2020) predicted that *Liriodendron chinense* suitable distribution area in China will continuously decrease with slight northward movement. Zhang et al. (2022) found that *Sophora flavescens* suitable habitat area in China has gradually decreased from the Last Glacial Maximum to future climate scenarios, with overall northward movement. However, other scholars have reached different conclusions: Chen et al. (2016) found that *Stipa breviflora* suitable area will increase under future climate scenarios and shift northward; Zhu et al. (2020) found that *Uraria* potential distribution area will increase under future climate conditions, with high-suitability areas shifting northward.

All wild *Cymbidium* species are listed in Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), and all except *C. lancifolium* are included in China's second batch of nationally key protected wild plants. The primary causes of endangerment, beyond extensive collection, are human destruction of habitats that completely eliminates growth space or fundamentally alters growing environments.

Based on potential distribution predictions, species showing expansion trends under future scenarios—including *C. lancifolium*, *C. lowianum*, *C. dayanum*, *C. macrorhizon*, *C. sinense*, *C. serratum*, *C. eburneum*, and *C. aloifolium*—require conservation efforts focused on protecting their existing habitats. In areas with dense *Cymbidium* distributions, national nature reserve areas should be expanded to reduce protection gaps, or provincial and county-level reserves upgraded to national status to eliminate threats from human economic activities, maintain stable and continuous habitats, and satisfy growth conditions required for epiphytic shrubs, thereby ensuring environments for pollinator insects. For species showing significant contraction such as *C. elegans*, *C. erythraeum*, *C. mannii*, and *C. floribludum*, stable future suitable areas identified through predictions may serve as climate change refugia requiring special habitat protection attention. Additionally, artificial propagation and reintroduction to original habitats or ex-situ conservation should be considered. In summary, potential distribution predictions can inform rational and effective conservation strategies for rare and endangered *Cymbidium* species.

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Appendix 1: Dynamics of Changes in Suitable Habitat Area of *Cymbidium* Under Different Climate Scenarios

Table 1 Information of samples used in the study

Species	Accession number	Genome size(bp)	GC content(%)	Habit
Cymbidium aloifolium	KC876122.1	-	-	Epiphytic
C. dayanum	MW160431.1	-	-	Epiphytic
C. eburneum	MK820374.1	-	-	Epiphytic
C. ensifolium	KU179434.1	-	-	Terrestrial
C. erythraeum	MK820373.1	-	-	Epiphytic
C. faberi	KR919606.1	-	-	Terrestrial
C. floribludum	MK848043.1	-	-	Epiphytic or rarely terrest
C. goeringii	KT722982.1	-	-	Terrestrial
C. hookerianum	MT800927.1	-	-	Epiphytic
C. iridioides	NC029711.1	-	-	Terrestrial
C. kanran	NC029712.1	-	-	Terrestrial or epiphytic
C. lancifolium	MT576628.1	-	-	Epiphytic
C. lowianum	KU179437.1	-	-	Epiphytic
C. macrorhizon	KC876126.1	-	-	Holomycotrophic
C. mannii	MT273089.1	-	-	Epiphytic
C. serratum	KC876123.1	-	-	Terrestrial
C. sinense	NC021432.1	-	-	Terrestrial
C. tracyanum	MK848065	-	-	Epiphytic
C. cyperifolium	-	-	-	Terrestrial or epiphytic
C. elegans	-	-	-	Epiphytic
Geodorum eulophioides	-	-	-	Terrestrial

Table 2 AUC of 20 *Cymbidium* species for the nine climate scenarios

Species	Current	SSP1−2.6	SSP5−8.5
		2030s	2050s
Cymbidium	-	-	-
C. aloifolium	-	-	-
C. cyperifolium	-	-	-
C. dayanum	-	-	-

Species	Current	SSP1−2.6	SSP5−8.5
C. eburneum	-	-	-
C. elegans	-	-	-
C. ensifolium	-	-	-
C. erythraeum	-	-	-
C. faberi	-	-	-
C. floribludum	-	-	-
C. goeringii	-	-	-
C. hookerianum	-	-	-
C. iridioides	-	-	-
C. kanran	-	-	-
C. lancifolium	-	-	-
C. lowianum	-	-	-
C. macrorhizon	-	-	-
C. mannii	-	-	-
C. serratum	-	-	-
C. sinense	-	-	-
C. tracyanum	-	-	-

Table 3 Main climatic factors used for simulating suitable area of *Cymbidium* species and their contribution rate

Variable code	Environmental variable	*Cymbidium*	*C. dayanum*	*C. eburneum*	*C. macrorhizon*	*C. serratum*	*C. sinense*	*C. aloifolium*	*C. lancifolium*	*C. lowianum*	*C. iridioides*	*C. tracyanum*	*C. erythraeum*	*C. elegans*	*C. cyperifolium*	*C. hookerianum*	*C. mannii*	*C. goeringii*	*C. faberi*	*C. kanran*	*C. ensifolium*	*C. floribludum*
Bio02	Mean Diurnal Range	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Bio03	Isothermality	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Bio04	Temperature seasonality	7.2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Variable code	Environmental variable	*Cymbidium*	*C. dayanum*	*C. eburneum*	*C. macrorhizon*	*C. serratum*	*C. sinense*	*C. aloifolium*	*C. lancifolium*	*C. lowianum*	*C. iridioides*	*C. tracyanum*	*C. erythraeum*	*C. elegans*	*C. cyperifolium*	*C. hookerianum*	*C. mannii*	*C. goeringii*	*C. faberi*	*C. kanran*	*C. ensifolium*	*C. floribundum*
Bio06	Min temperature of coldest month	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Bio07	Temperature annual range	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Bio11	Temperature of Coldest Quarter	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Bio12	Annual precipitation	28.4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Bio14	Precipitation of Driest Month	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Bio16	Precipitation of Wettest Quarter	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Variable code	Environmental variable	*Cymbidium*	*C. bicolor*	*C. dayanum*	*C. macrorhizon*	*C. serratum*	*C. sinense*	*C. aloifolium*	*C. lancifolium*	*C. lowianum*	*C. iridioides*	*C. tracyanum*	*C. erythraeum*	*C. elegans*	*C. cyperifolium*	*C. hookerianum*	*C. mannii*	*C. goeringii*	*C. faberi*	*C. kanran*	*C. ensifolium*	*C. floribundum*
Bio17	Precipitation of driest quarter	46.3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Bio18	Precipitation of warmest quarter	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Note: Numbers in the table represent the contribution rate (%) of each climatic factor to the species distribution simulation; "-" indicates low contribution rate.

Figure 1 ROC curve verification of Maxent prediction under the current climate scenario [Figure 1: see original paper]

Figure 2 Contribution of various environmental variables based on Jackknife test [Figure 2: see original paper]

Figure 3 Single variable response curve [Figure 3: see original paper]

Figure 4 Potential distribution pattern of *Cymbidium* under different climatic scenarios [Figure 4: see original paper]

Figure 5 Change of the suitable range of *Cymbidium* in different periods [Figure 5: see original paper]

Figure 6 Potential distribution pattern of *C. dayanum* under different climatic scenarios [Figure 6: see original paper]

Figure 7 Potential distribution pattern of *C. erythraeum* under different climatic scenarios [Figure 7: see original paper]

Figure 8 Potential distribution pattern of *C. elegans* under different climatic scenarios [Figure 8: see original paper]

Figure 9 Potential distribution pattern of *C. goeringii* under different climatic scenarios [Figure 9: see original paper]

Figure 10 The consensus phylogenetic tree of *Cymbidium* species based on whole chloroplast genome sequences [Figure 10: see original paper]

Appendix 1: Dynamics of Changes in Suitable Habitat Area of *Cymbidium* Under Different Climate Scenarios

Detailed tables showing area changes for each species under different climate scenarios are provided in the supplementary materials.

Note: Figure translations are in progress. See original paper for figures.

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