Potential Geographic Distribution of the Genus Tugarinovia in China under Climate Change Scenarios (Postprint)

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Abstract

Tugarinovia Iljin is an endemic genus in the Alashan Desert, and predicting the impact of climate change on its potential geographic distribution is crucial for its conservation. Based on 34 current distribution points and 22 environmental variables of Tugarinovia in China, this study utilized the Maximum Entropy (MaxEnt) model to simulate changes in distribution patterns under current and future (2050s, 2070s) conditions across three Shared Socioeconomic Pathways (SSP1-2.6, SSP2-4.5, and SSP5-8.5). The Area Under the ROC Curve (AUC) value was used to evaluate the model' s predictive performance, while the jackknife method and comprehensive contribution rate were employed to analyze the main environmental factors affecting its distribution. The results indicate that: (1) The MaxEnt model exhibits high simulation accuracy (AUC=0.992); elevation, precipitation in the warmest quarter, precipitation in the coldest quarter, and mean annual temperature are the dominant environmental factors influencing the geographic distribution of Tugarinovia. (2) The current suitable habitat area and high-suitability habitat area of Tugarinovia are both relatively small, with suitable habitat area of 37.08$×10^{4}$ km^2 and high-suitability habitat area of 6.89$×10^{4}$ km^2, mainly distributed in a fragmented pattern along the Yinshan and Helan Mountains. (3) Under the three future climate scenarios, the high-suitability habitat area of Tugarinovia shows an overall increasing trend, with a particularly substantial increase under the SSP5-8.5 climate scenario; the centroid of its suitable habitat area primarily shifts eastward (toward Alashan Left Banner).

Full Text

Potential Geographical Distribution of Tugarinovia in China Under Climate Change Scenarios

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Abstract

Tugarinovia Iljin is a genus endemic to the Alashan Desert in China. Predicting the impact of climate change on its potential geographical distribution is crucial for its conservation. This study, based on 34 distribution sites of Tugarinovia in China and 22 environmental variables under three Shared Socioeconomic Pathways (SSP1-2.6, SSP2-4.5, and SSP5-8.5), utilized the Maximum Entropy (MaxEnt) model to simulate current and future (2050s and 2070s) changes in the distribution pattern of Tugarinovia in China. The model' s predictive performance was evaluated using the area under the ROC curve (AUC) value, and the dominant environmental factors influencing its distribution were analyzed using the Jackknife method and comprehensive contribution rates. The results indicate: (1) The MaxEnt model demonstrated high simulation accuracy (AUC = 0.992); altitude, warmest quarter precipitation, coldest quarter precipitation, and annual mean temperature are the dominant environmental factors affecting the geographical distribution of Tugarinovia. (2) Currently, both the suitable and highly suitable areas for Tugarinovia are relatively limited, with a total suitable area of 37.08×10^4 km^2 and a highly suitable area of 6.89×10^4 km^2, primarily distributed in a fragmented pattern along the Yinshan and Helan Mountains. (3) Under the three future climate scenarios, the highly suitable area for Tugarinovia shows an overall increasing trend, with a particularly large increase under the SSP5-8.5 scenario; the centroid of its suitable area mainly migrates eastward.

Keywords: Tugarinovia; climate change; MaxEnt model; environmental variables; suitable area

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Introduction

Climate change poses severe threats to species distribution patterns, phenology, population size, and ecosystem structure and function, presenting enormous challenges to global biodiversity. Species unable to adapt to climate change may experience population declines and migration, with endangered species being particularly sensitive [1-2]. Therefore, under the background of global climate change, identifying priority areas for biodiversity conservation and enhancing the protected area network are effective means to promote the adaptation of China' s nature reserves to climate change [3]. Currently, China' s nature reserves are established based on current species distributions. However, species habitats are dynamic and continuously change with external environmental conditions, making it difficult to meet conservation needs under future climate change scenarios [4]. As an indicator of species endangerment status, species distribution warrants attention regarding potential distribution changes under future climate impacts, which is crucial for biodiversity conservation and sustainable utilization of plant resources [5].

Ecological niche models are mathematical models based on niche theory that use existing species distribution points and environmental data with specific algorithms to reflect potential distribution changes under different climate scenarios [6]. Among various niche models—including the Maximum Entropy model (MaxEnt), BIOCLIM, Ecological Niche Factor Analysis (ENFA), CLIMEX, and Genetic Algorithm for Rule-set Prediction (GARP)—MaxEnt demonstrates superior prediction accuracy [7] and has been widely applied to study potential distributions of numerous species [8-9]. MaxEnt performs well in simulating suitable habitat changes even with small samples, limited species records, or incomplete data [10] and is currently widely used in biodiversity conservation, phylogeography, ecology, invasion biology, and research on climate change impacts on species distributions [11-12].

Tugarinovia Iljin belongs to the Asteraceae family and is a genus endemic to both the Alashan Desert and the Mongolian Plateau [13]. The genus includes Tugarinovia mongolica and Tugarinovia ovatifolia. Tugarinovia mongolica is distributed in North Alashan and East Gobi, listed as a national second-class key protected wild plant and classified as vulnerable in China' s threatened species list [14-15]; Tugarinovia ovatifolia is distributed in the low mountain hills of southern Alashan. The genus is primarily found in Darhan Mumingan Joint Banner, Urad Middle Banner, Urad Rear Banner, northern Alxa Left Banner, Zhuozi Mountain, Helan Mountain, and other areas, playing an important role in studying the flora of central Asia and the phylogeny of Asteraceae [16]. Due to climate change, human activities, and reproductive biological barriers, this species has a narrow distribution and declining population size. Current research on Tugarinovia has focused on taxonomy [13], anatomy [17-20], embryology [21-23], biogeography [16], and phylogeography [24]. However, studies on the suitable area range of Tugarinovia in China and its response to climate change are scarce.

This study, based on existing field survey data and literature for Tugarinovia distribution points, combined with environmental factors such as climate and topography, used ArcGIS software and the MaxEnt 3.4.1 model to simulate the potential distribution of Tugarinovia in China under current and future (2050s and 2070s) conditions across three Shared Socioeconomic Pathways (SSP1-2.6, SSP2-4.5, and SSP5-8.5). We analyzed the dominant environmental factors affecting its potential geographical distribution and explored changes in suitable areas and spatial patterns under different future climate scenarios, aiming to provide a theoretical basis for wild resource conservation and nature reserve construction.

1.1 Data Sources and Processing

Distribution data for Tugarinovia were obtained from: (1) field surveys conducted in 2019 and 2021, supplemented by population surveys; (2) the Global Biodiversity Information Facility (GBIF, https://www.gbif.org/); (3) the Chinese Virtual Herbarium (CVH, https://www.cvh.ac.cn); (4) the National Specimen Information Infrastructure (http://www.nsii.org); and (5) relevant published literature. After removing duplicate records and distribution information that could not be precisely georeferenced to the county level, 34 valid distribution points were retained (Fig. 1), with 21 derived from field surveys and 13 from literature and online databases. These data were compiled in Excel and saved in CSV format.

Current climate data (1970-2000) were downloaded from the WorldClim database (http://www.worldclim.org/), including 19 bioclimatic variables (Bio1-Bio19) and elevation data at 2.5 arc-minute resolution. Using ArcGIS software, slope and aspect were extracted from the elevation data. Future climate data were derived from the sixth phase of the Coupled Model Intercomparison Project (CMIP6), specifically the CSM2-MR model, under three emission scenarios: SSP1-2.6 (updated version of RCP2.6, representing low forcing), SSP2-4.5 (updated version of RCP4.5, representing medium forcing), and SSP5-8.5 (updated version of RCP8.5, representing high forcing) [25]. All environmental variables for current and future periods were processed in ArcGIS with a spatial resolution of 2.5 arc-minutes.

1.2 Environmental Variable Screening

To reduce model overfitting caused by multicollinearity among environmental variables, we performed Pearson correlation analysis using the Hmisc package in R. For variable pairs with correlation coefficients $|r| > 0.8$, we retained the variable with higher contribution rate that better reflected Tugarinovia's growth requirements [26]. This resulted in 11 environmental variables for subsequent modeling: elevation, slope, aspect, annual mean temperature (Bio1), mean diurnal range (Bio2), temperature seasonality (Bio4), mean temperature of the coldest quarter (Bio11), precipitation seasonality (Bio15), warmest quarter precipitation (Bio18), coldest quarter precipitation (Bio19), and annual precipitation (Bio12).

1.3 MaxEnt Model Construction and Operation

Tugarinovia distribution point data and screened environmental variables were imported into MaxEnt 3.4.1 to simulate potential distributions under current and future (2050s and 2070s) climate scenarios. Parameter settings: 75% of distribution data as training set and 25% as testing set [27]; 10 repeated runs with other parameters set to default. The Jackknife test was used to assess the importance of environmental variables for species distribution modeling. Model performance was evaluated using the area under the receiver operating characteristic curve (AUC), where values >0.9 indicate excellent prediction [28].

1.4 Suitable Area Classification and Centroid Migration Analysis

Based on field surveys and the current distribution status of Tugarinovia in China, suitable areas were classified into four categories: highly suitable (0.5-1.0), moderately suitable (0.3-0.5), low suitable (0.1-0.3), and unsuitable (0-0.1) [29]. Potential suitable area maps for current and future climate scenarios were generated. MaxEnt outputs in ASCII format were converted to raster files in ArcGIS 10.6. Using the SDM toolbox, raster files were converted to binary files [30], and the Distribution Changes Between Binary SDMs tool calculated suitable area changes across periods and scenarios. The centroid of suitable areas was determined, and migration paths were mapped.

2.1 MaxEnt Model Accuracy Assessment

Using 34 current distribution points and 11 screened environmental variables, MaxEnt 3.4.1 modeled and predicted the potential distribution of Tugarinovia in China. Ten replicate runs yielded an average AUC of 0.992, indicating excellent model performance and highly accurate predictions of Tugarinovia' s potential geographical distribution (Fig. 2).

2.3 Current Suitable Areas of Tugarinovia in China

The current suitable area for Tugarinovia in China is 37.08×10^4 km^2, accounting for approximately 3.9% of China' s land area. The distribution is primarily in Inner Mongolia, with smaller areas in Ningxia, Gansu, and Xinjiang. The highly suitable area is 6.89×10^4 km^2, constituting 18.6% of the total suitable area. Both moderately and low suitable areas exceed the highly suitable area, accounting for 20.3% and 61.1% of the total suitable area, respectively. The highly suitable area is concentrated along the Yinshan and Helan Mountains, specifically in Urad Rear Banner, Urad Middle Banner, and Urad Front Banner of Bayan Nur City; Alxa Left Banner and Alxa Right Banner of Alxa League; Otog Banner and Wuhai City of Ordos; Shizuishan, Yinchuan, and Zhongwei cities in Ningxia; Baiyin City in Gansu; and Aksu City in Xinjiang (Fig. 1; Table 2).

2.4 Potential Suitable Area Changes Under Future Climate Scenarios

Under the three future climate scenarios, highly, moderately, and low suitable areas show different trends (Table 2). Under SSP1-2.6, total suitable area increases by 3.3% in the 2050s and 5.1% in the 2070s compared to current conditions. Highly suitable area increases by 3.3% in the 2050s and 5.1% in the 2070s, while moderately and low suitable areas show initial decreases followed by increases.

Under SSP2-4.5, total suitable area decreases by 2.1% in the 2050s but increases by 1.2% in the 2070s. Highly suitable area increases by 8.5% in the 2050s and 11.2% in the 2070s. Moderately suitable area decreases in the 2050s then increases in the 2070s, while low suitable area shows a consistent decreasing trend.

Under SSP5-8.5, total suitable area increases by 15.3% in the 2050s and 20.2% in the 2070s. Highly suitable area increases by 15.3% in the 2050s and 20.2% in the 2070s, moderately suitable area increases in both periods, while low suitable area decreases (Fig. 4).

2.5 Migration Direction of Suitable Area Centroids

Under SSP1-2.6, the centroid migrates westward in the 2050s and continues westward in the 2070s. Under SSP2-4.5, the centroid shifts southeast in the 2050s, then northwest in the 2070s, approaching the current centroid. Under SSP5-8.5, the centroid migrates northeast in the 2050s, then southeast in the 2070s, moving toward Alxa Left Banner in Inner Mongolia (Fig. 5).

3 Discussion

The MaxEnt model achieved high prediction accuracy (AUC = 0.992), with results largely consistent with Tugarinovia' s actual distribution in China. In China' s arid northwest region, temperature and precipitation are critical environmental factors determining species potential distribution and growth [31-32]. Sample size and species ecological characteristics significantly affect model accuracy; species with narrow ecological amplitudes and specialized habitats typically yield higher accuracy than those with broad amplitudes and high environmental tolerance [33-34]. This study demonstrates that MaxEnt is suitable for simulating Tugarinovia' s potential distribution in China.

Precipitation-related factors (warmest and coldest quarter precipitation) cumulatively contributed 42.5% to the model, making them crucial for Tugarinovia' s distribution. This aligns with the biological characteristics of the genus, which has specific water requirements; populations decline when precipitation is insufficient. Altitude contributed 22.4%, also a key factor, as Tugarinovia grows on dry, rocky residual hills or gravel slopes at 1000–1500 m, with most populations around 1200 m, validating the Jackknife results.

Climate warming may shrink suitable distribution ranges, disrupt gene flow, and reduce genetic diversity, though some studies show increased genetic diversity and expanded ranges [35]. Molecular evidence indicates Tugarinovia populations maintain high genetic diversity with significant inter-population differentiation [24]. Under future climate scenarios, highly suitable areas will increase by 3.3%–

20.2%, with the largest increase (20.2%) under SSP5-8.5 in the 2070s, likely related to rising temperatures and increasing annual precipitation in northwest China [36-37]. However, despite increased suitable areas, the overall distribution remains limited and fragmented. Field surveys found Tugarinovia ovatifolia only in the low mountain hills of Zhuozi Mountain-Helan Mountain with sparse populations, facing severe threats from mining development in Wuhai. Currently, no nature reserves exist for Tugarinovia. We recommend establishing nature reserves in highly suitable areas to protect native habitats and maintain population stability, while collecting germplasm resources from populations heavily impacted by human activities and using artificial propagation to expand distribution ranges and mitigate climate change impacts.

Global climate change is driving many plant species toward higher latitudes and elevations [1,36,41], but responses vary among species [42]. This study predicts that under SSP2-4.5 and SSP5-8.5 scenarios, Tugarinovia' s suitable area centroid will migrate to lower elevations; under SSP5-8.5, it will also shift to lower latitudes, approaching Alxa Left Banner by the 2070s. Climate change will drive suitable habitats toward lower elevations and latitudes, confirming that migration ability is a key factor in species adaptation. However, this study only considered environmental and topographic variables; actual distributions are also influenced by soil types, human disturbance, biological factors (e.g., interspecific competition), and biotic interactions, which should be integrated in future research to improve prediction accuracy.

4 Conclusions

MaxEnt is suitable for simulating Tugarinovia' s potential distribution in China. The dominant environmental variables are warmest quarter precipitation, altitude, coldest quarter precipitation, and annual mean temperature, with altitude and precipitation factors having the greatest influence. Current highly suitable areas align well with actual distributions, primarily in Urad Rear Banner, Urad Middle Banner, and Urad Front Banner of Bayan Nur City; Alxa Left and Right Banners; Otog Banner and Wuhai City of Ordos; Shizuishan, Yinchuan, and Zhongwei in Ningxia; and Baiyin in Gansu. Although highly suitable areas will increase under future climate scenarios, the overall distribution remains limited and fragmented. We recommend implementing both in-situ and ex-situ conservation measures in highly suitable areas to expand population distribution.

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Figure and Table Captions:

[Figure 1: see original paper] Current distribution sites and suitable distribution areas of Tugarinovia in China

[Figure 2: see original paper] ROC curve of the MaxEnt model

[Figure 3: see original paper] Importance of environmental variables for Tugarinovia distribution based on Jackknife test

Environmental variables and their contribution rates

Potential suitable areas of Tugarinovia in China in different periods (10^4 km^2)

[Figure 4: see original paper] Potential distribution areas of Tugarinovia in China under different climate scenarios

[Figure 5: see original paper] Migration paths of Tugarinovia in China under different climate scenarios

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