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Assessment of the Potential Distribution of the Rare Species *Astragalus Knorringianus* in the Nurata Nature Reserve Based on a Bioclimatic Model

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Abstract Based on the BIOCLIM model using 17 ecological factors, the potential distribution area of the rare endemic of the Northwest Pamir-Alai, *Astragalus knorringianus* Boriss., was assessed within the Nurata State Nature Reserve. It was found that the most significant ecological factors influencing the species' distribution are the mean temperature of the wettest quarter, daily and annual temperature variability, slope aspect, solar radiation, and the minimum vegetation index. The results of the bioclimatic modeling showed that the most favorable habitats for the species are located on the southern dry slopes of the Nurata Ridge, with a total area of 35.78 km ²(9.4% of the total area of the Nurata Reserve and its buffer zone).

Keywords Range, Bioclimatic modeling, Nature reserve, Climate change, Red Book, Rare species, Ecological niche, Ecological factor, Endemic, Uzbekistan

1. Introduction

Plants are of key importance to life on Earth and are integral components of ecosystems. At the same time, anthropogenic pressure on the plant world continues to intensify globally, resulting in the process of biodiversity loss reaching catastrophic proportions. Another global factor threatening biodiversity is climate change. Currently, due to the cumulative impact of anthropogenic and climatic factors, many endemic and stenotopic species have become endangered [1,2,3]. In this regard, targeted research into the ecology and biology of narrowly distributed endemics and the phenomenon of endemism as a whole represents a pressing scientific issue [4,5,6]. One of the most modern methods is the identification of bioclimatic niches for rare and vulnerable species, the determination of ecological factors influencing the distribution of these species, and the assessment of potential species responses to climate change using computer modeling [7,8].

The Nurata State Nature Reserve is located in the northwestern foothills of the Pamir-Alay mountain system, in the central part of the Nurata Range. The current area of the reserve is 22.18 km ², and together with the buffer zone, the total area under study is 380.83 km ². The central part of the Nurata Range, including the territory of the reserve and its buffer zone, is an internationally recognized key biodiversity area within the Central Asia Mountains Global Biodiversity Hotspot [9,10]. This region is rich in rare and endemic species, with a flora endemism rate of 2.7% [11]. In this regard, the Nurata Reserve is of great importance for the conservation of biological diversity in the Republic of Uzbekistan, including many endemic, rare, and endangered plant species.

In this study, based on the BIOCLIM model, the potential distribution range of *Astragalus knorringianus* Boriss. a rare endemic of the North-Western Pamir-Alai, listed in the Red Book of the Republic of Uzbekistan with status 2 [12] was analyzed within the territory of the Nurata State Nature Reserve. The environmental factors favorable for this species have been identified.

2. Research Methods

As the subject of the study, one of the rare, narrowly endemic species of the legume family (Fabaceae) was chosen *Astragalus knorringianus* Boriss. a perennial, nearly stemless, gray-green, closely pubescent herbaceous plant, 5–10 cm tall, hemicryptophyte. The leaves are 2–5 cm long, imparipinnate. The leaflets are arranged in 7–9 pairs, linear or linear-lanceolate, 5–11 mm long and 0.5–1.5 mm wide. Flower stalks are 2–5 cm long. There are 2–3 light yellow flowers. The standard is 32–37 mm long, and the calyx is 17–20 mm long. The pods are linear, closely covered with

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white and black hairs, up to 7 cm long and 4 mm wide, with a short beak. It blooms from March to April and bears fruit from May to June. It reproduces by seeds. It is distributed in the northwestern spurs of the Pamir-Alai (the Nurata, Turkestan, and Malguzar ranges). It grows on finely earthy, rocky, and gravelly soils, in the foothills, the lower and middle mountain belts, at elevations ranging from 497 to 1,728 meters above sea level.

In this study, for the first time, the method of bioclimatic modeling using the BIOCLIM software package was applied to determine the ecological niche and potential distribution range of *Astragalus knorringianus* within the Nurata Reserve. The BIOCLIM program approximately defines the bioclimatic contour and summarizes the climatic conditions in the specified areas [13]. The indicators obtained from the GEE platform were processed to achieve a spatial resolution of 1 km. In the study, based on the SRTM digital elevation model, a number of topographic indicators were obtained that characterize the features of the terrain (elevation above sea level, slope, aspect, as well as the topographic wetness index) [14]. The Terra Climate dataset covers a range of variables reflecting environmental and climate parameters, based on regular measurements of relevant data. Annual solar radiation, maximum solar radiation, and sunshine hours were selected as such variables. Since most satellite data with long time series are characterized by low spatial resolution, inconsistent accuracy, and lack of comparability, the CHIRPS dataset [15] was used in this study. Atmospheric parameters such as cloud cover, wind speed, and surface temperature were taken from ERA5- Land [16]. Soil parameters were downloaded from the SoilGrids database [17]. From the WorldClim v2.1 database, among 19 bioclimatic variables, bio_2, bio_3, bio_8, and bio_19 were selected [18]. To identify the main ecological factors shaping species habitats, a Principal Component Analysis (PCA) was conducted. This analysis makes it possible to reduce the correlation between numerous ecological variables and determine their principal directions of influence [19].

Selection of environmental variables and the BIOCLIM model

Figure 1. Selected environmental variables for the BIOCLIM model

In this study, 41 environmental variables and the occurrence points of *Astragalus knorringianus* were introduced into the BIOCLIM model. In the correlation analysis, the relationships among the 41 variables were assessed using the Pearson coefficient. As a result of this assessment, 24 variables with high correlation ($r \geq |0.7|$) were excluded, leaving 17 factors with low intercorrelation for modeling. The remaining factors (bio_2, bio_3, bio_8, bio_19, wet_season_Rad, SOC, sand, silt, clay, twi, Slp, Asp, Cloud, Wnd_speed, avg_wet_Prcp, min_NDVI, max_NDVI) provide independent ecological information for the accurate and reliable assessment of the species' ecological niche through bioclimatic modeling (Figure 1).

3. Results

Based on the results of the BIOCLIM model, the potential distribution range of *Astragalus knorringianus* was determined within the study area of the Nurata Reserve and its buffer zone (with a total area of 380.83 km ²). According to the model analysis, the most favorable habitats for this plant species, which provide optimal ecological conditions, total 35.78 km ² (9.40% of the study area). The area of unfavorable territories for the species, where the necessary ecological conditions are absent, amounts to 345.05 km ² (90.60%) (Figure 2).

The most favorable habitats are mainly located on slopes of moderate steepness with south-western and western exposure. The actual occurrence points of the species (blue dots) closely match the suitable habitats predicted by the model, indicating a high level of model accuracy (Figure 2).

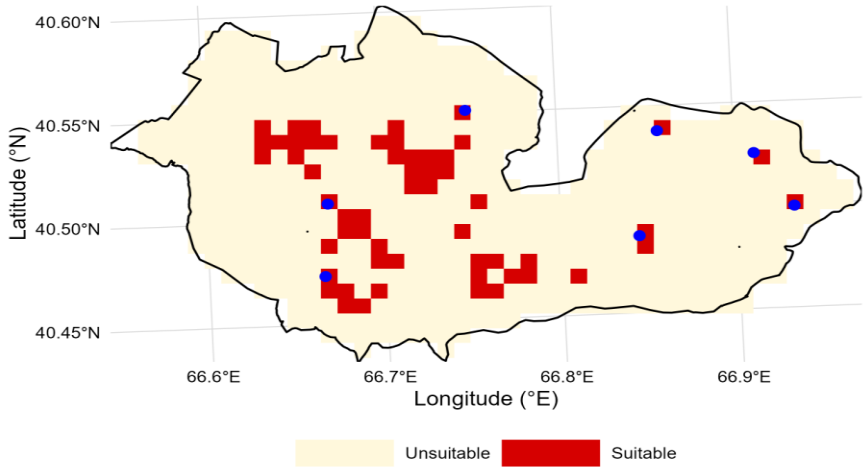

Figure 2. Potential distribution of *Astragalus knorringianus* in the Nurata Reserve based on the BIOCLIM model

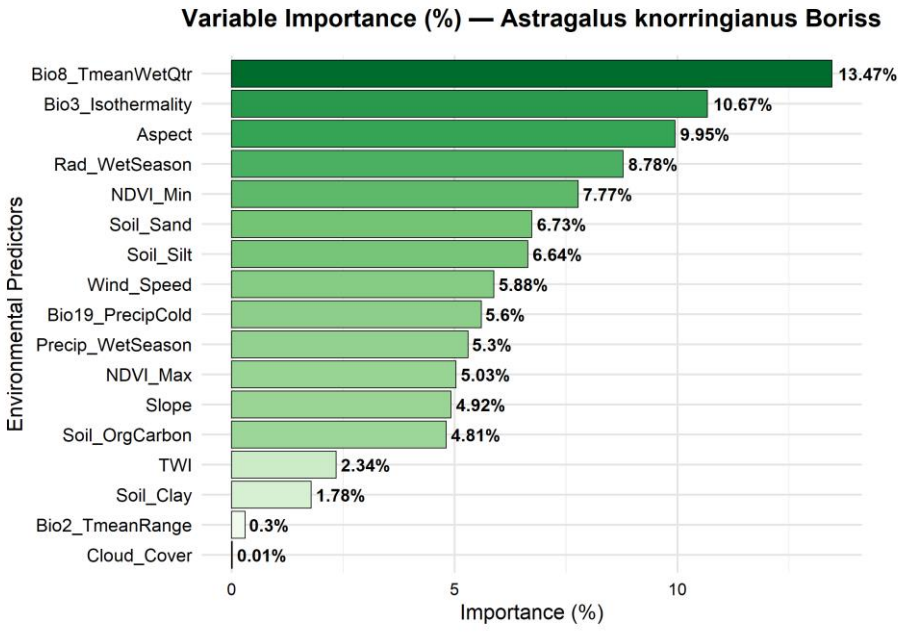

Figure 3. The influence of environmental factors on the distribution of *Astragalus knorringianus*

Analysis of Environmental Factors

According to the results obtained using the BIOCLIM model, the spatial distribution of *Astragalus knorringianus* is most influenced by factors primarily related to the climatic and topographical groups. A total of 17 environmental factors were analyzed, among which the following were found to be the most significant:

1. The most important factors: Bio8_TmeanWetQtr (13.47%) – the average temperature of the wettest quarter is the factor exerting the greatest influence on the distribution of this species. This indicates that the species actively develops under moderately warm and moderately humid conditions during the spring-summer period. Bio3_Isothermality (10.67%) – the ratio of daily to annual temperature variation points to the species' sensitivity to temperature stability. The species is resilient to sharp temperature fluctuations, but demonstrates optimal growth in consistently warm conditions. Aspect (9.95%) – the exposure of the terrain determines the amount of sunlight. The species is predominantly found on sunny, warm southern and southwestern slopes. Rad_WetSeason (8.78%) – solar radiation during the wettest season, as a factor enhancing the process of photosynthesis, increases plant biomass. NDVI_Min (7.77%) – the minimum vegetation index reflects the ability of the species to retain green biomass even during dry periods, which indicates good adaptation to the arid conditions of the region.
2. Moderately important factors: Soil_Sand (6.73%) and Soil_Silt (6.64%) – the mechanical composition of the soil plays an important role in the development of the species' root system and its water permeability. This species prefers to grow on sandy and light loamy soils, that is, on well-drained substrates. Wind_Speed (5.88%) – wind speed contributes to the natural dispersal of seeds and the formation of the microclimate. Bio19_PrecipCold (5.6%) – the amount of precipitation during the coldest period affects the species' winter dormancy, but its overall significance is relatively low.
3. Minor factors: Cloud_Cover (0.01%) and Bio2_Tmean Range (0.3%) – the influence of these factors is very low, as the species is adapted to sunny regions with sharp temperature fluctuations. Soil_Clay (1.78%) and TWI (2.34%) – factors associated with moisture accumulation – have relatively little significance, since the species is adapted to living in dry conditions (Figure 3).

Ecological interpretation

The results obtained show that *Astragalus knorringianus* is a xerophytic species adapted to semi-desert foothill ecosystems, to dry open habitats with high insolation, good ventilation, high temperatures, and relatively low precipitation. The optimal living conditions for this species are sunny southern slopes.

The onset and active phase of vegetation in the species are associated with the moist and warm spring period (Bio8_TmeanWetQtr).

These results show that the narrow geographic range of *Astragalus knorringianus* is due to its limited ecological tolerance, while the species is highly adapted to its habitat. The small distribution area and narrow ecological niche indicate that climate change and human activities (such as livestock grazing, construction, and erosion) may pose a serious threat to the natural populations of this species.

PCA – Principal Component Analysis

As mentioned above, as a result of the Pearson correlation calculation for 41 environmental factors, 24 highly correlated variables were excluded (including Bio1, Bio4, Bio12–Bio18, Elev, pH, annualRad, sunshine_duration, meanNDVI, and others). Thus, the following 17 factors were used for PCA:

Climatic factors: Bio2 (mean diurnal temperature range), Bio3 (isothermality), Bio8 (mean temperature of the wettest quarter), Bio19 (precipitation of the coldest quarter), Wet_season_Rad, Wind_speed.

Topographic factors: Aspect (exposure), Slope, TWI (topographic wetness index).

Soil factors: SOC (soil organic carbon content), Clay, Sand, Silt.

Factors related to vegetation and cloud cover: NDVI_min, NDVI_max, Cloud, Avg_wet_Prcp.

This approach made it possible to reduce multicollinearity and simplify the ecological interpretation of the PCA results. The components obtained through PCA reflect the main ecological gradients of the species' niche that is, they enable visual analysis of the factors that have the greatest influence on its growth [19].

According to the results of the PCA, the first two principal components (PC1 and PC2) explain 69% of the total variance: PC1 accounts for 50.5%, and PC2 for 18.5%. PC1 mainly shows a positive correlation with the variables NDVI_Max, Wind_Speed, Slope, and Soil_Clay, which indicates the species' adaptation to frequent strong winds, soil density, and steep terrain. PC2 is associated with the influence of Precip_WetSeason and Soil_Sand, reflecting wet conditions and sandy soils. The species' position on the biplot is located near the vectors Slope, Wind_Speed, and NDVI_Max. This indicates its adaptation to growing on dry, open, and well-lit slopes under strong winds. Its opposite orientation with respect to the vectors Soil_OrgCarbon and Bio19_PrecipCold confirms the species' distribution on poor soils with low organic content and in conditions with little precipitation (Figure 4).

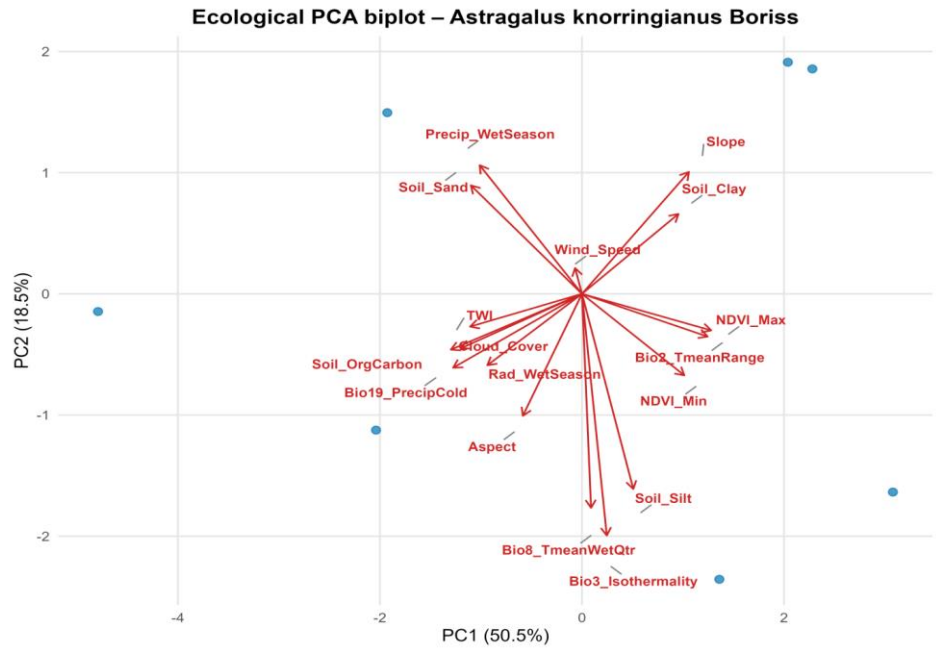

Figure 4. PCA analysis of *Astragalus knorringianus*

Thus, the results of the PCA analysis showed that *A. knorringianus* is a typical xerophyte adapted to conditions of moisture deficiency, high insolation, and high temperatures during the growing season. The PCA results confirmed that the probability of this species spreading is highest on open southern dry slopes of the Nurata Ridge.

4. Conclusions

The results of the study showed that the rare endemic species *Astragalus knorringianus* is a typical xerophyte, found within a limited ecological range. It was established that the main bioclimatic factors determining the species' distribution are the average temperature of the wettest quarter, daily and annual temperature variability, terrain exposure, solar radiation, and the minimum vegetation index. The most favorable habitats for the species are located on open, dry southern slopes of the Nurata Ridge with light, well-drained soils. Because the species has a limited range and a narrow ecological niche, climate change and anthropogenic pressure can pose a significant threat to its populations. The ecological characteristics of the species must be taken into account when developing a targeted conservation strategy.

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