Forecast of climate change impact on habitat suitability of *Linaria uralensis* Kotov (Scrophulariaceae) in the Southern Urals

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**Abstract.** Rare plant species are the most vulnerable components of vegetation cover under climate change. The aim of this paper was to model the influence of climatic changes on the habitat suitability for *Linaria uralensis* Kotov in the Southern Urals. The MaxEnt program was used for modeling. Climate variables from CHELSA BIOCLIM and topographic variables of the digital elevation model were used as predictors. An ensemble of four future climate models under the RCP4.5 (moderate) and RCP8.5 (high) climate change scenarios was used to estimate potential changes in habitat suitability in the middle and second half of the 21st century. The modeling results showed that the species *L. uralensis* has a fairly high drought tolerance. The habitat conditions of this species will potentially be preserved in the area of its current distribution. Under moderate and high climate change some increase in the areas of high and medium habitat suitability is expected. Thus, it can be predicted that existing protection measures for this species will be sufficient, and there will be no need for additional conservation measures.

1. **Introduction**

Since the middle of the last century, there have been strong climatic changes in the form of increasing temperatures and changes in the amount and redistribution of summer and winter precipitation [1]. Their impact on vegetation is predicted to continue in the future [2]. Rare relict and endemic species formed during the Pleistocene period are the most vulnerable components of the vegetation cover under climate change. One of them is *Linaria uralensis* Kotov, a taprooted perennial short-lived herbaceous plant [3]. The species is included in the Red Data Books of the Republic of Bashkortostan (under the name *Linaria altaica* Fisch. ex Kuprian.) [4], Chelyabinsk [3] and Orenburg Oblasts [5]. *L. uralensis* grows in the Bashkir Pre-Urals (in the eastern part of the Obshchyi Syrt), in the Southern Urals (in the southern part of the Zilaire Plateau, Dzyautube Ridge), in the Trans-Urals (lower reaches of the Tanalyk River and in the east of the Ural River in Chelyabinsk Oblast at the same latitude) and further south in Orenburg Oblast (mainly in the Sakmara-Ural Rivers interfluve). The northern border of the species' range runs along the Obschiy Syrt on the latitude of the mouth of the Urginka River in the Republic of Bashkortostan. [4]. In the southeast, *L. uralensis* is bordered by the closely related species *L. altaica*, and in the north by *Linaria debilis* Kuprian. It forms hybrid forms with both of these species [6]. *L. uralensis* was studied by M. I. Kotov [7] and M. C. Knyazev [8] as an...
independent species, while L. A. Kupriyanova considered the differences between *L. uralensis* and *L. altaica* insignificant and considered them as one species, *L. altaica* [9, 10]. Thus, *L. uralensis* can be considered either a relic of the Pleistocene complex or an endemic species of the Southern Urals, which formed in the Pleistocene period. For a final decision on the independence of *L. uralensis* it is probably necessary to conduct additional studies using modern genetic methods.

The species *L. uralensis* is found in lowland petrophytic steppes, screes or cliffs on carbonate (limestones, carbonatized sandstones) and siliceous sedimentary and effusive rocks. It can settle on stony substrates of anthropogenic origin (roadside quarries and excavations) [4]. One of the mechanisms of this species adaptation to xerophytic conditions is its rather early seasonal growth (the species can start flowering at the end of May) [4]. The distribution of *L. uralensis* is limited by weak ecological plasticity, low competitiveness (always found among highly sparse vegetation), as well as grazing and mining of crushed stone [5]. Thus, estimating the stability of habitat conditions under climate change is crucial for the conservation of the species.

2. Problem Statement

Methods of mathematical modeling are widely used to predict possible changes in habitat conditions for rare species during climatic changes [11]. Among them, the most widely used is the maximum entropy method implemented in the MaxEnt program [12]. Modeling results allow us to identify priority populations for the conservation of these species and develop recommendations for the reintroduction of the most valuable populations [13]. The aim of the research is to model the influence of climatic changes on the habitat suitability for *L. uralensis* in the Southern Urals.

3. Materials and Methods

The coordinates of geographically referenced locations of *L. uralensis* from herbarium collections of UIB UFRC RAS (UFA) and GBIF were used as presence data in the modeling of habitat suitability [14]. A total of 47 locations were used, including 29 located in the Republic of Bashkortostan and 18 located in the Orenburg and Chelyabinsk oblasts. The MaxEnt v3.4.1k program was used for modeling [12]. Climate variables from CHELSA BIOCLIM were used as predictors for model construction [15], as well as three variables of the digital elevation model (GMTED2010): maximum, minimum, and mean elevation above sea level [16]. In the case of the correlating values between the environmental variables greater than or equal to 0.8, one of the variables was excluded [17]. In this case, preference for further use was given to the variables with larger contribution to the model identified at the preliminary stage. In other cases, the parameters reflecting quarterly rather than monthly characteristics of temperature and precipitation were preferred. Two scenarios, RCP4.5 and RCP8.5, corresponding to moderate and high climate change, were used to estimate the expected changes in the suitability of growing conditions in the 2040-2060 period (hereafter the 2050s) and the 2061-2080 period (hereafter the 2070s) of the 21st century [18]. An ensemble of four climate change models [19] (CCSM4 [20], NorESM1-M [21], MIROC-ESM [22], INMCM4 [23]) was used to predict the future distribution of the species [24]. The AUC indicator was used for statistical evaluation of the model. [20]. We applied the "Maximum test sensitivity plus specificity" threshold as the lowest limit for the habitat suitability. We used five-fold cross-validation, and the final model was the mean of the five folds. In the final models, the habitat suitability was divided into three groups: low, medium, and high. The area covered by each suitability level was calculated using the tools "Raster Calculator" and "Polygonize" in the QGIS v3.14.1 program. To interpret the results, the predicted change in temperature and precipitation compared to the current climatic conditions was calculated for the current distribution area using data from the corresponding CHELSA BIOCLIM sets.

4. Results and discussion

The AUC value of the model of the current potential range of *L. uralensis* was 0.997, which represents a high level of model quality. Four environmental variables had the highest contribution to the model: the difference between maximum and minimum elevation within one pixel, precipitation of driest
month (February), temperature seasonality (standard deviation of monthly average temperatures) and isothermality (the ratio of the mean diurnal range to the annual temperature range). The last two variables represent the continentality of the climate. The cumulative contribution of these variables in the model was 89.3%.

The results of modeling of the species’ current potential range are shown in figure 1. Habitat suitability is divided into four gradations: unsuitable (0-0.29), low suitable (0.29-0.55), medium suitable (0.55-0.81), and high suitable (0.81-1.00).

![Figure 1. Current potential range of Linaria uralensis Kotov in the Southern Urals. White circles indicate known locations of the species used in the modeling.](image)

The main part of the potential range of *L. uralensis* covers the southern regions of the Republic of Bashkortostan, including the Zilairskoe plateau, the Pre-Urals and Trans-Urals, as well as the northern and northwestern part of the Orenburg Oblast. The area of the species also enters the Trans-Ural area in the Chelyabinsk Oblast. In the west, it continues along the Bugulminsko-Belebeyevskaya Upland and reaches Saratov Oblast, where it overlaps with the range of the closely related species *Linaria odora* (M.Bieb.) Fisch. High suitable habitats of the species are mostly concentrated in the Republic of Bashkortostan and the Orenburg Oblast. They include areas of steppe vegetation confined on moderate slopes, strong slopes and moderately steep slopes of different exposure according to the classification of V. K. Zhuchkova and E. M. Rakovskaya [25]. The exceptions are two localities, one of which is confined to the flat hilltop and the other is located in the flat rocky bank of the Tanalyk River. Locations with low habitat suitability are confined to flat areas and gentle slopes. The connection of habitat suitability with the slope is due to higher water and wind erosion on steep slopes, which leads to the formation of petrophytic steppe areas with sparse grass vegetation, which is the main habitat of this species. During modeling, one of the presence points was 35 km beyond the northern boundary of the potential range of the species in the Trans-Ural region on the disturbed rocky section of the gas pipeline passing through the distribution area of the species. The low habitat suitability in this locality is compensated by low competition from other herbaceous species.
Figure 2 shows the change in habitat suitability of *L. uralensis* in the middle and the second half of the 21st century under moderate (RCP4.5) and high (RCP8.5) climate change scenarios and figure 3 shows the change in the areas of parts of the range with different habitat suitability for this species. Under moderate climate change, a drastic increase in the areas with low habitat suitability is projected by the middle of the 21st century, mainly along the perimeter of the expanding range. In the central part of the range the suitability of some areas with low habitat suitability will increase, which will lead to the increase in the area with medium to high habitat suitability. In the second half of the 21st century the areas with medium habitat suitability will tend to decrease, and the areas with highly suitable habitat will decrease almost to the current level.

![Figure 2. Forecast of habitat suitability for *Linaria uralensis* Kotov in the Southern Urals under moderate (RCP4.5) and high (RCP8.5) climate change scenarios in the middle (the 2050s) and the second half (the 2070s) of the 21st century. White circles indicate known locations of the species.](image_url)

In case of high climate change an even larger increase in the area of areas with low and medium habitat suitability is projected by the middle of the 21st century. However, the distribution of high habitat suitability areas will increase to a lesser extent compared to the increase in distribution under moderate climate change during the same time period. Further, in the second half of the 21st century, the distribution areas of all three habitat suitability groups are projected to decline drastically, but will nevertheless be larger than at present.

The majority of current localities of *L. uralensis* are located mainly in the steppe zone. The main limiting factors for the *L. uralensis* species and other steppe species competing with it are precipitation...
Figure 3. Changes in the areas of low, medium, and high habitat suitability for *Linaria uralensis* Kotov under moderate (RCP4.5) and high (RCP8.5) climate change in the middle (the 2050s) and second (the 2070s) half of the 21st century.

and temperature, which determine the rate of evaporation of precipitation. Table 1 shows the changes in mean annual and summer temperature and precipitation amounts, which largely explain the change in habitat suitability under climate change. The table shows that under a moderate climate change, the average annual precipitation increases while it remains at the same level in the warmest quarter. The increase in habitat suitability of *L. uralensis* under moderate and high climate change can be explained by an increase in soil moisture content in the spring. The increase in the climate aridity in summer is less significant, since the species is characterized by rapid seasonal development. This is indirectly confirmed by the lower variability of the most rocky areas with high habitat suitability compared to the areas with medium and low habitat suitability of this species. The reasons for the decrease in areas of medium and high habitat suitability by the 2070s under both climate change scenarios are unclear. But it can be assumed that a significant role will be played by the reduction of snow accumulation in the winter period due to the increase in temperature and faster drying of the soil in the spring period.

Table 1. Predicted temperature and precipitation increases in the area of modern distribution of *Linaria uralensis* Kotov under moderate (RCP4.5) and high (RCP8.5) climate change in the middle (the 2050s) and in the second (the 2070s) half of the 21st century compared to the present time.

| Scenario (year) | Temperature change, °C | Precipitation change, mm |
|-----------------|------------------------|--------------------------|
|                 | Annual mean temperature | Mean temperature of warmest quarter * | Annual precipitation | Precipitation of warmest quarter * |
| RCP4.5 (2050)   | 2.3                    | 2.1                      | 29.9                | 6.6                        |
| RCP4.5 (2070)   | 2.7                    | 2.3                      | 41.8                | 5.5                        |
| RCP8.5 (2050)   | 2.8                    | 2.8                      | 7.38                | 2.8                        |
| RCP8.5 (2070)   | 4.3                    | 4.2                      | 41.2                | 3.6                        |

Note: * the warmest quarter in the study area is June-August.
5. Conclusions
The modeling results showed that the species *L. uralensis* has a fairly high drought tolerance. The preservation of growth conditions of this species in the area of its current distribution can be predicted under moderate and high climate change, as well as some increase in the areas with high and medium habitat suitability. Summer droughts will result in increased grazing pressure, which will increase soil erosion on steep and gentle slopes, which will stimulate seed dispersal of this species on outcrops of stony soil. In this regard, it can be predicted that existing conservation measures for *L. uralensis* will be sufficient and there will be no need for additional conservation measures.

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