# EVALUATING THE VULNERABILITY OF ENDANGERED *Allium* species (Amaryllidaceae) TO CLIMATE CHANGE IN CENTRAL ASIA

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**Abstract.** This study evaluates the impact of climate change on the distribution of ten threatened *Allium* species (*A. pskemense*, *A. viridiflorum*, *A. majus*, *A. praemixtum*, *A. giganteum*, *A. isakulii*, *A. backhousianum*, *A. eremoprasum*, *A. aflatunense*, and *A. alaicum*) in Central Asia. We employed MaxEnt modeling and ENVIREM datasets to predict current and future habitat suitability, classifying areas into high, moderate, low, and unsuitable categories. Key environmental factors influencing species distributions included the Topographic Wetness Index (TopoWet), Terrain Roughness Index (TRI), Minimum Temperature of the Coldest Month (Bio6), and Precipitation of the Coldest Quarter (Bio19). Our findings show that, except for *A. eremoprasum*, *A. isakulii*, *A. praemixtum*, and *A. pskemense*, most species will experience a reduction in highly suitable habitats under future climate scenarios, with shifts toward less suitable areas. Lithosols and calcic xerosols were the predominant soil types in areas of high habitat suitability. The study underscores the vulnerability of these species to climate change and anthropogenic pressures such as grazing, bulb collection, and habitat degradation. We recommend targeted conservation strategies, including habitat restoration, expansion of protected areas, and community-based management, to mitigate these threats. This research provides a scientific basis for conservation efforts, emphasizing the importance of integrating both climatic and topographic factors in species distribution modeling for the long-term survival of Central Asia's endemic *Allium* species.

**Key words:** Central Asia; climate change; ENVIREM datasets; habitat suitability; maxEnt modeling; protected areas.

## INTRODUCTION

In the context of accelerating climate change, species are expected to undergo evolutionary and ecological shifts to survive in rapidly changing environments. These adaptations manifesting in altered physiological functions and morphological traits will influence species' geographic ranges, community compositions, and distribution patterns [19]. The spatial distribution of plant species is shaped by a complex interplay of abiotic variables such as temperature, precipitation, and soil composition, alongside biotic factors including human-induced habitat modifications [6, 22].

Recent advancements in ecological modeling particularly the integration of niche modeling with geographic information systems (GIS), have made it possible to precisely predict suitable habitats under current and future climatic scenarios. Among species distribution models (SDMs), MaxEnt (Maximum Entropy Modeling) has emerged as one of the most robust tools for modeling the distribution of rare or endangered species with limited occurrence data [13, 20]. MaxEnt's advantage lies in its high predictive accuracy and minimal data requirement (as few as five presence records), relying solely on species occurrence coordinates and environmental variables [6].

The genus *Allium* L. (Amaryllidaceae), one of the largest monocotyledonous genera, comprises around 1,000 species distributed across 15 subgenera and 85 sections [10, 14, 36]. This genus includes economically and ecologically significant taxa such as onion, garlic, leek, and shallot. Central Asia, especially Uzbekistan, is a biodiversity hotspot for endemic *Allium* species. However, this region is also facing acute ecological threats from logging, agriculture, mining, and overgrazing [12, 16].

According to Uzbekistan's National Red Book [15] fourteen *Allium* species are currently listed as endangered, including *A. praemixtum*, *A. aflatunense*, *A. pskemense*, *A. alaicum*, *A. botschantzevii*, *A. bakhousianum*, *A. majus*, *A. giganteum*, *A. isakulii*, *Allium caspium* subsp. *baissunense*, *A. ravenii*, *A. decoratum*, *A. eremoprasum*, and *A. viridiflorum* [15] (Fig. 1). These species are under mounting pressure not only from environmental stressors but also from anthropogenic activities such as medicinal harvesting and livestock overgrazing. Several species are currently protected within designated state nature reserves, including the Nuratau, Surkhan, Chatkal Biosphere, Hissar, and Kitab Geological Reserves [15].

Despite their ecological and economic significance, the current and future distribution patterns of these red-listed *Allium* species remain poorly understood. In particular, the influence of key environmental drivers on habitat suitability under climate change scenarios has not been comprehensively assessed. To address these gaps, this study employs MaxEnt modeling to: (1) to map the current potential geographic distribution of red-listed *Allium* species in Uzbekistan; (2) to identify the most influential environmental variables governing their distributions; (3) project future changes in habitat suitability under climate change scenarios; (4) to recommend high-priority conservation areas, including protected reserves. (5) to cross-reference suitable habitats with soil data to refine site-specific conservation strategies.

The findings from this research will provide an empirical foundation for biodiversity conservation, habitat restoration, and regional biogeographical studies involving *Allium* species in Central Asia.

## MATERIALS AND METHODS

*Study area*

On the interior of the Eurasian continent, Central Asia is 9950 km long and 8650 km wide. It has a total area of 4,003,451 $km^2$ and includes five countries: Kazakhstan, Uzbekistan, Tajikistan, Turkmenistan, and Kyrgyzstan. It extends from the Caspian Sea in the west to China and Mongolia. The lowest and highest points is 154 m to 7495 m, respectively [20]. It encompasses an overall land of 36-55 N and 45-90 E (Fig. 2). The terrain of Central Asia is incredibly diverse, with high mountain passes cutting across enormous mountain ranges including the Tian Shan, Hindu Kush, and Pamirs (Figs. 2-3). The climate of Central Asia is arid and semiarid [4]. The environment is extremely vulnerable to regional climate change and

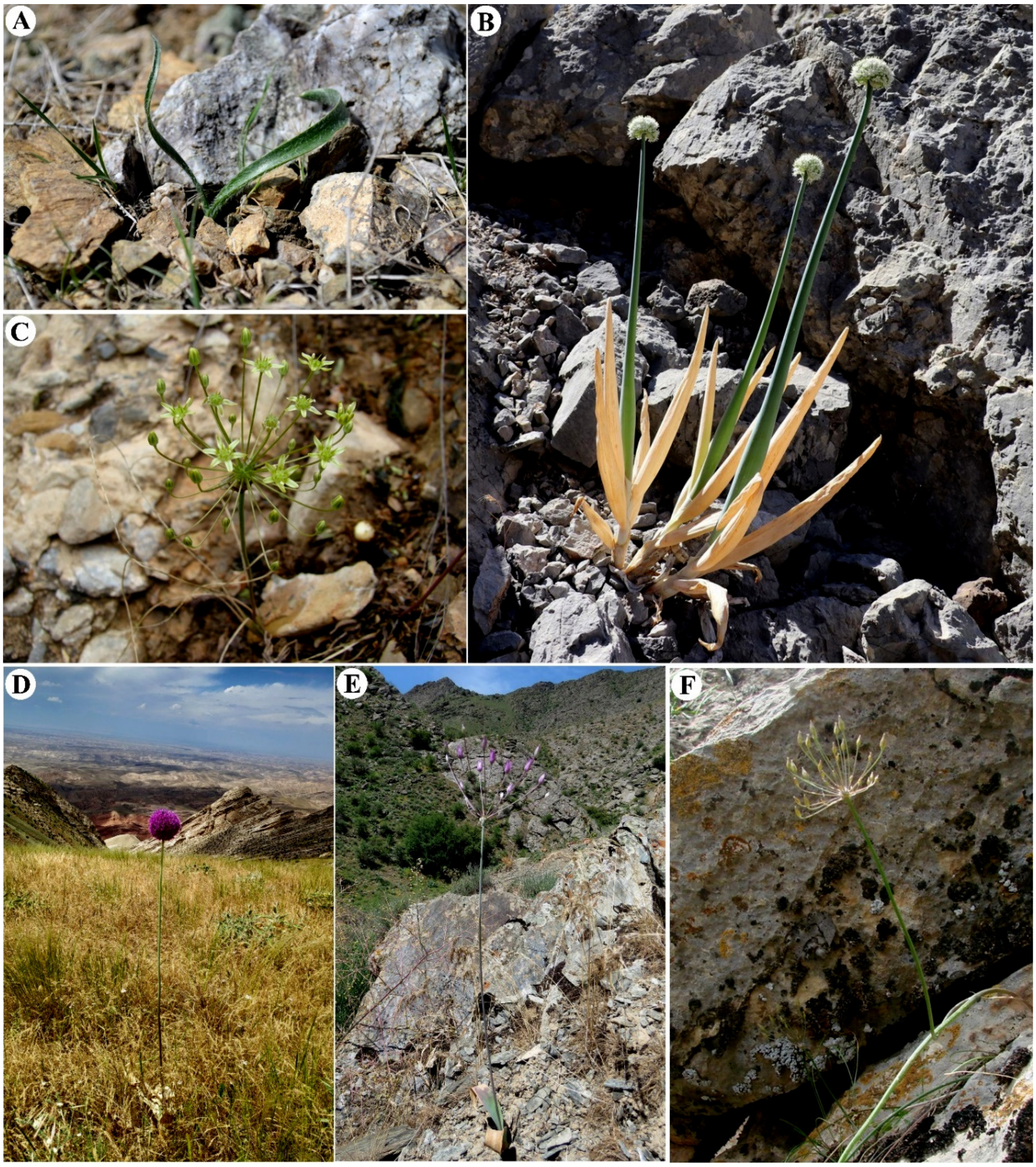


**Figure 1.** Some species of the genus *Allium* in their natural habitats: **A-** *A. alaicum*, Kyrgyzstan, Osh region, northern macroslope of the Alai Range, 8 April 2014 (photo by A. Naumenko). **B-** *A. pskemense*, Uzbekistan, Tashkent region, Pskemsky range, Badaksay gorge, about 1750 m above sea level, rocks, 20 July 2022 (photo by N. Beshko). **C-** *A. viridiflorum*, Kyrgyzstan, Chatkal Range, Sary-Chelek Reserve, 9 June 2011 (photo by G. Lazkov). **D-** *A. giganteum*, Uzbekistan, Surkhandarya region, Babatag ridge, env. mountains Besharcha, tract Taldybulak, vys. about 1500 m a.s.l., among xerophilic shrub woodlands, 25 May 2019 (photo by N. Beshko). **E-** *A. isakulii*, Uzbekistan, Nuratau ridge, Nurata reserve, Madzherumsay tract, about 900 m above sea level, rocky slope, 20 May 2017 (photo by N. Beshko). **F-** *A. eromoprasum*, Uzbekistan, Nurata mountains, Aktau ridge, Bakhiltau mountains, Charkhansay tract, on a rock, 830 m a.s.l. 10 May 2013 (photo by N. Beshko).

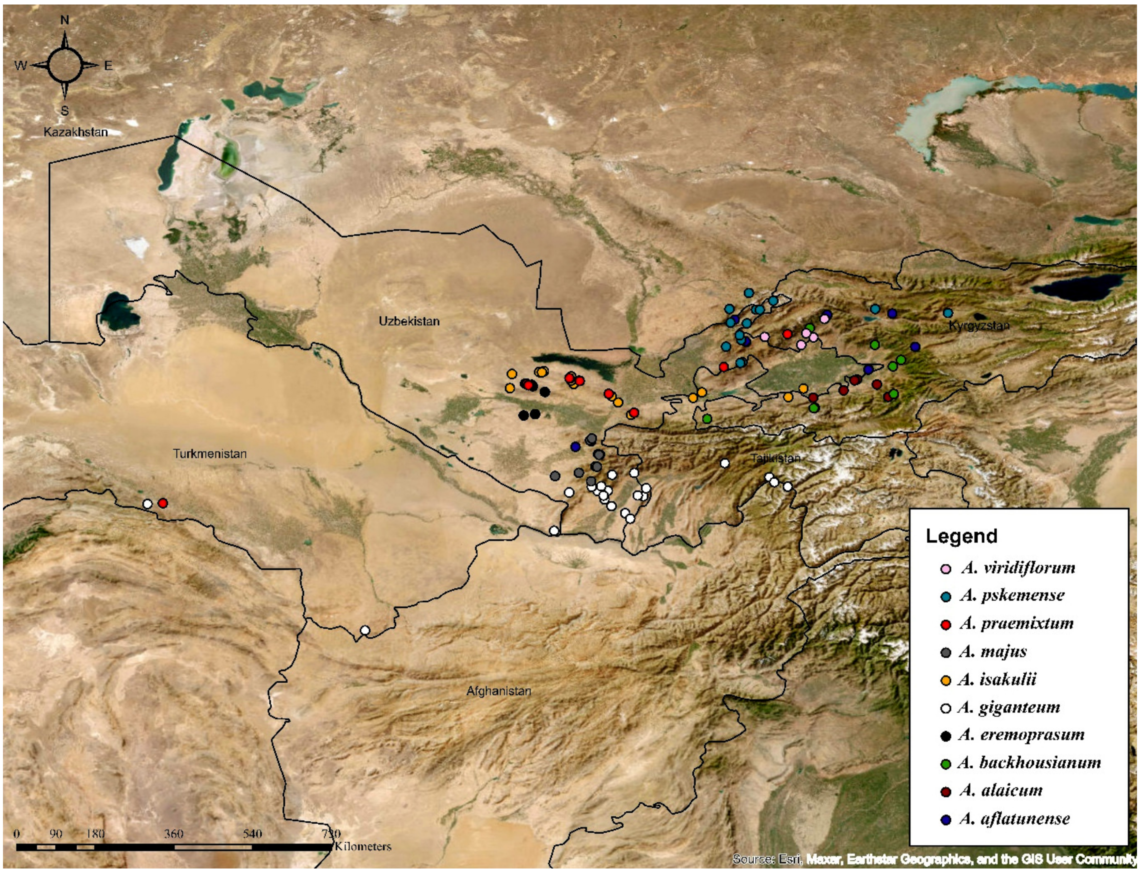


**Figure 2.** The study area and the occurrence sites of ten species of the genus *Allium* thorough Central Asia.

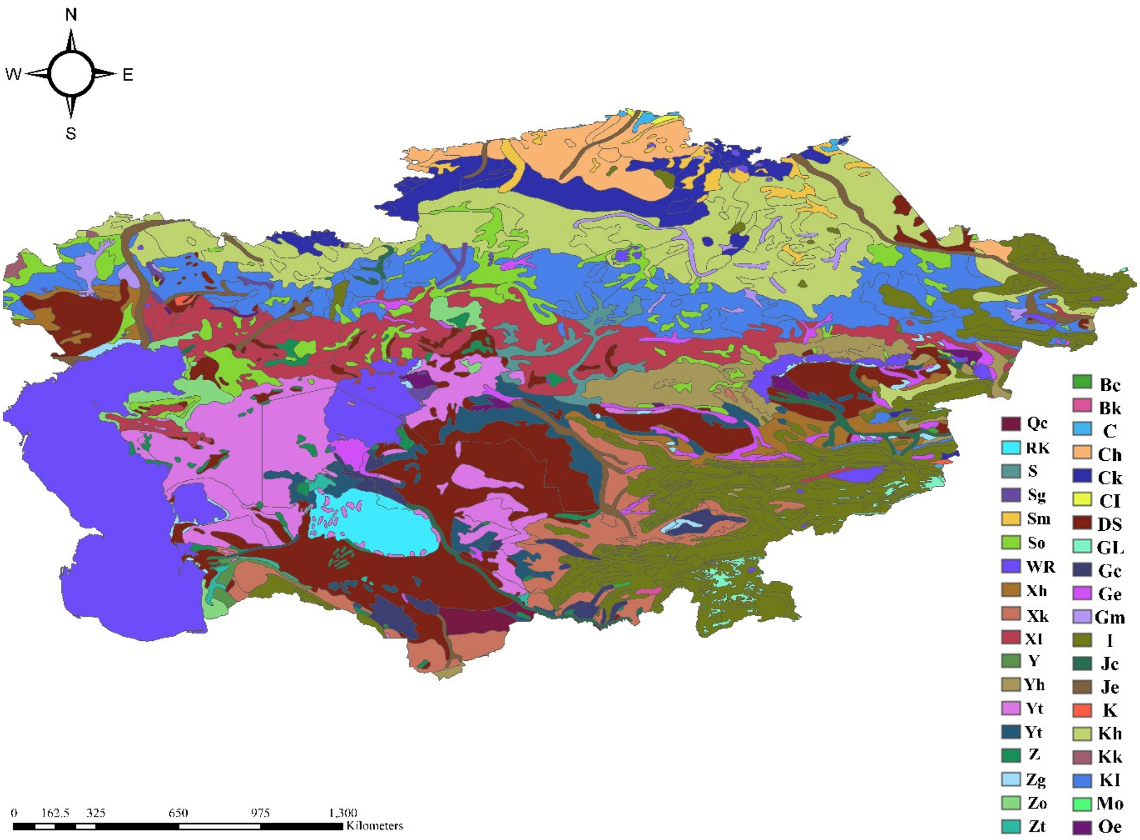


**Figure 3**. Soil type classification (DOMSOI) of the territory of Central Asia according to FAO (www.fao.org/ag/agl/agll/key2soil.stm). Bc - Zt = Soil unit; DS = Dunes or shifting sands, WR = Inland water or ocean.

to shifting weather patterns [4]. Despite its predominantly arid and semiarid climate conditions typically considered limiting for biodiversity Central Asia is recognized as a significant center of plant diversity [4] (Fig. 2).

*Data*

For the SDM analysis, the occurrence records of *A. pskemense, A. viridiflorum, A. majus, A. praemixtum, A. giganteum, A. isakulii, A. backhousianum, A. eremoprasum, A. aflatunense* and *A. alaicum* used in the distribution modeling were obtained from the herbarium TASH, the public databases of the Global Biodiversity Information Facility [11]; Plantarium [28]. We exluded the unknown and repeated sampling points, and finally, 20, 22, 13, 13, 8, 9, 8, 15, 6 and 11 distribution points, respectively that could be utilized for the MaxEnt model program were kept. For the environmental variables, 19 historical global bioclimatic variables were obtained from the Worldclim database [8] with the time range of 1970–2000. Future climate data were obtained from Model for Interdisciplinary Research on Climate (MIROC6) for SSP245, which included the year 2081−2100 (Supplementary table 1). The topographic factors such as elevation, slopes, and aspect were obtained from the digital elevation model (DEM) from Wordclim database [8]. The topographic wetness index (TopoWet) was utilized to account for the soil water content. In addition to the above mentioned bioclimatic data, we also used Terrain roughness index (TRI) and these two variables (TRI and TopoWet) are from ENVIREM bioclimatic dataset. In order to study the potential suitable habitats with high resolution the data pixel dimension of all bioclimate variable used were 30 Arc Seconds (1 km). We utilized ArcGIS10.8 to visualize the geographical distribution of species (Fig. 2). The soil data was obtained from the FAO official website the Digital Soil Map of the World. The territory of Central Asia was extracted to evaluate the soil type classification (DOMSOI) of Central Asia (Fig. 3). The data on protected areas was downloaded from The World Database on Protected Areas [27] and the map of Protected Areas of Uzbekistan was accordingly created (Fig. 4).

*Environmental variable screening*

For screening environmental variables, correlation analysis of climate data was carried out using SDMtoolbox v2.4 tool package (ArcGIS software) for the Pearson coefficient [5]. Data on species distribution and initial climate variables were input into MaxEnt to determine the initial contribution rate, and very low contribution rate variables and correlation values (greater than 0.8) were eliminated since correlated variables for MaxEnt modeling cannot be used [7].

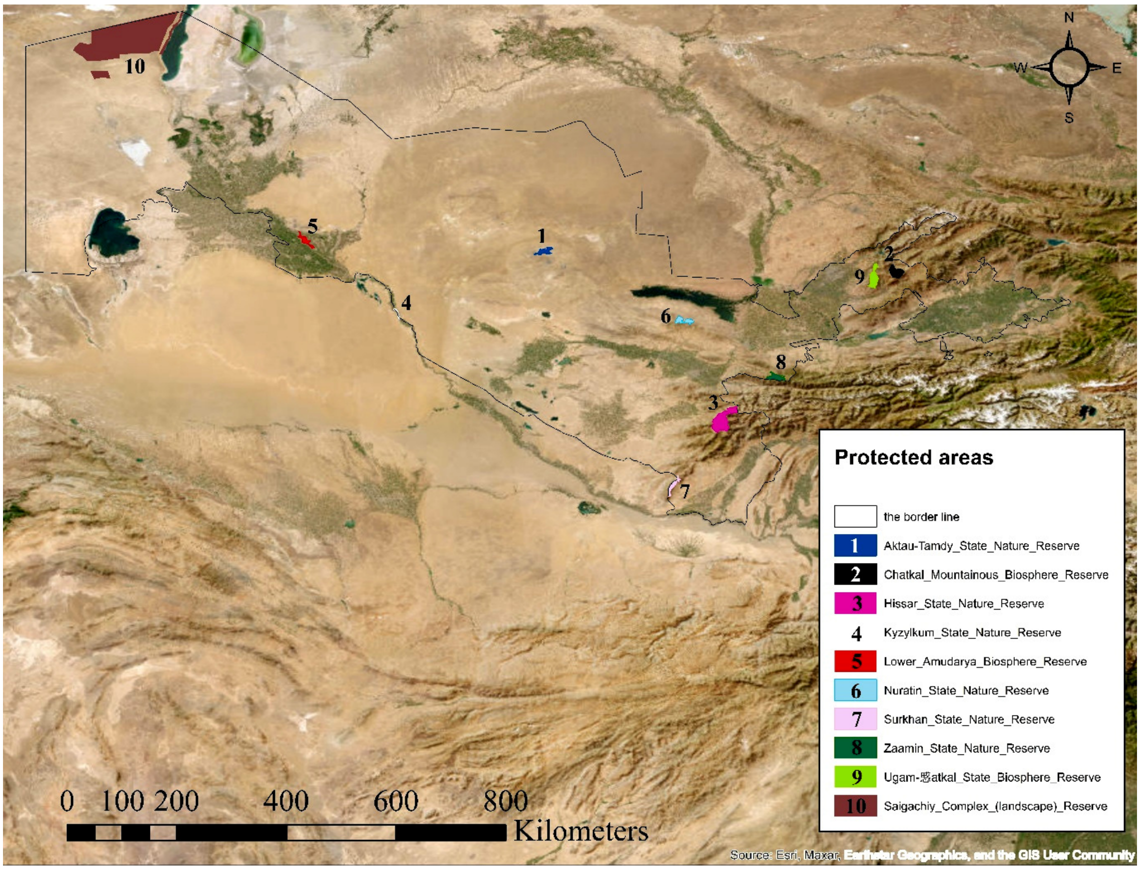


**Figure 4**. The protected areas of Uzbekistan (State Nature Reserves).

*Maximum entropy model and parameter setting*

MaxEnt software (version 3.4.1) came from the American Museum of Natural History [2]. The species distribution data were converted into csv files for MaxEnt modeling, and the ArcGIS format conversion function transformed the tiff variable layer into the ASC layer that MaxEnt program requires. The software's "Sample" and "Environmental layers" were imported with the data on species distribution and climate variables, respectively. By selecting "Create response curves," response curves for climate variables were drawn, and variable importance was calculated using Jackknife analysis. The predictions were drawn by selecting the option "Make pictures of predictions". Output format and file type were default values. "Random seed" was set as a random proportion, "Regularization Multiplier" was set to 1, and the number of "Replicates" was 10, meaning the model could run 10 times. During the operation, the training parameter and the test parameter were set to 75% and 25%, respectively, the number of iterations was set to 10,000.

*Model Accuracy Evaluation*

Jackknife analyses were conducted to assess the significance of each variable. The AUC values were utilized to evaluate the performance of the model. The AUC value varies from 0 to 1, with a higher value indicating a more accurate prediction made by the model. If the AUC number is less than 0.5, the model simulation fails because it is inadequate to the random simulation. If it is between 0.5 and 0.7, the model running is poor. If it is between 0.7 and 0.9, the model simulation impact is considered average. The model's simulation accuracy is considered better and more capable of accurately representing the species' potential distribution if the value exceeds 0.9 [26].

*Division of Suitable Habitats*

ArcGIS 10.8 software was employed to visualize the simulation results and delineate habitat suitability. The natural-breaks classification method (Jenks) was applied to categorize the species into four suitability levels based on gradients: highly suitable habitat (0.65–0.99), moderately suitable habitat (0.34–0.65), low suitability habitat (0.12–0.34), and unsuitable habitat (0–0.12). Subsequently, the Reclassify tool in ArcGIS 10.8 was used to calculate the distribution areas corresponding to each suitability grade.

## RESULTS

*Accuracy of the maxent model*

Using the MaxEnt model, the potentially suitable habitats for *A. isakulii, A. giganteum, A. aflatunense, A. majus, A. alaicum, A. backhousianum, A. eremoprasum, A. pskemense, A. viridiflorum,* and *A. praemixtum* were predicted, and the ROC curve was used to verify the accuracy of the simulated distribution. The average AUC for the prediction model of suitable habitats for these species under the current climate were 0.988, 0.974, 0.953, 0.988, 0.897, 0.980, 0.961, 0.994, 0.994, and 0.983, respectively (Supplementary figures 1, 2). These results indicate that the model's prediction performance was excellent, with high accuracy and reliability.

*The variables' contribution to suitability*

Percent contribution (PC) and permutation importance (PI) are key metrics for assessing the relative importance of environmental variables in determining the suitability of habitats for a given species. The larger the values for these indicators, the more influential the environmental variables are in predicting habitat suitability. The results of our analysis indicate the significant contribution of various environmental factors to the predicted suitable habitats of the studied *Allium* species, based on both percent contribution and permutation importance (Fig. 5). For *A. isakulii*, the most influential environmental variables include the terrain roughness index (TRI), with a percent contribution (PC) of 33.8% and a permutation importance (PI) of 6.9, and the mean temperature of the coldest quarter (Bio11), which has a PC of 30.5% and a PI of 83.1. These variables play critical roles in shaping the habitat suitability of this species. In *A. giganteum*, the terrain roughness index (TRI) emerges as the most important variable, contributing 34.7% to the habitat suitability, with a PI of 16.7. Additionally, the minimum temperature of the coldest month (Bio6) contributes 27.8% (PC) and 64.6 (PI), and the precipitation of the coldest quarter (Bio19) has a PC of 18.4% with a relatively lower PI of 1.6. For *A. aflatunense*, the SAGA-GIS topographic wetness index (TopoWet) proves to be the most influential factor, with a PC of 34.4% and a PI of 1.9. Additionally, temperature seasonality (standard deviation ×100) (Bio4) contributes 16.7% (PC) and 53.8 (PI), underlining the significant role of seasonal temperature variation in determining the species' distribution. In *A. majus*, the temperature annual range (Bio5-Bio6) (Bio7) stands out with a substantial PC of 48.4% and a PI of 15, followed by the SAGA-GIS topographic wetness index (TopoWet), contributing 22.1% to the suitability model with a PI of 27.6. For *A. alaicum*, the SAGA-GIS topographic wetness index (TopoWet) is the most influential environmental variable, accounting for 49.9% of the habitat suitability (PC) and 38.4 (PI). In comparison, precipitation seasonality (coefficient of variation) (Bio15) contributes 17.4% (PC) and 39.2 (PI). Regarding *A. backhousianum*, the SAGA-GIS topographic wetness index (TopoWet) has the highest contribution (44.9% PC, 17.3 PI), followed by the mean temperature of the driest quarter (Bio9), which contributes 24.4% to the model and has a PI of 64.7. For *A. eremoprasum*, the SAGA-GIS topographic wetness index (TopoWet) plays the most significant role in determining habitat suitability, contributing 37.3% (PC) and 41.5 (PI). The minimum temperature of the coldest month (Bio6) also significantly influences suitability (25.6% PC, 16.6 PI), as does aspect (23.3% PC, 23.8 PI). In *A. praemixtum*, the SAGA-GIS topographic wetness index (TopoWet) contributes 37.3% (PC) and 29.7 (PI), while temperature seasonality (standard deviation ×100) (Bio4) also significantly affects habitat suitability (20.3% PC, 29.7 PI). For *A. pskemense*, the SAGA-GIS topographic wetness index (TopoWet) remains a key variable, contributing 34.3% (PC) and 22.5% (PI). Additionally, annual precipitation (Bio12) accounts for 22.5% of the habitat suitability (PC) with a PI of 8.4. Finally, for A. viridiflorum, the SAGA-GIS topographic wetness index (TopoWet) is one of the primary determinants of habitat suitability (23.6% PC, 2.4 PI). Precipitation seasonality (coefficient of variation) (Bio15) and temperature seasonality (standard deviation ×100) (Bio4) also significantly affect its distribution, with contributions of 23.0% (PC, 21.5 PI) and 20.4% (PC, 62.7 PI), respectively. The full range of environmental variables influencing the distributions of the studied *Allium* species is illustrated in Figure 5, highlighting the complex interactions of climatic and topographic factors in determining species' habitat suitability.

*Current and future potential suitable areas and soil data*

The current and future suitable habitat areas for various *Allium* species in Central Asia were assessed and classified according to four suitability categories: high, middle, low, and unsuitable. The following species were analyzed: *A. pskemense, A. viridiflorum, A. majus, A. praemixtum, A. giganteum, A. isakulii, A. backhousianum, A. eremoprasum, A. aflatunense*, and *A. alaicum*. The results are summarized in Figures 6-11 and Supplementary Table 2, which depict the spatial distribution and suitability of each species' habitat in Central Asia under both current and future environmental conditions. According to MaxEnt modeling, the current suitable habitat (low, midde and highly suitable) for *A. pskemense* spans approximately 114,718 km², representing 2.5% of Central Asia's total land area. Highly suitable habitats for this species are primarily found in the Fergana Range, Chatkal Range, and Alai Mountains. In terms of habitat classification, moderately suitable areas span 25,050 km² (0.547% of the study area), and low-suitability areas cover 75,069 km² (1.63%). Additionally, small patches of highly suitable habitats are located along the eastern part of Afghanistan. Under future environmental conditions, the habitat area of high suitability shrinks significantly to 0.28%, while areas classified as moderately suitable increase to 0.554%. Similarly, low-suitability habitats grow to 1.674% (Fig. 7). These shifts suggest a reduction in the ideal climatic conditions for *A. pskemense* and an expansion of marginally suitable habitats. The predominant soil types found in the most suitable areas is lithosols (Fig. 7).

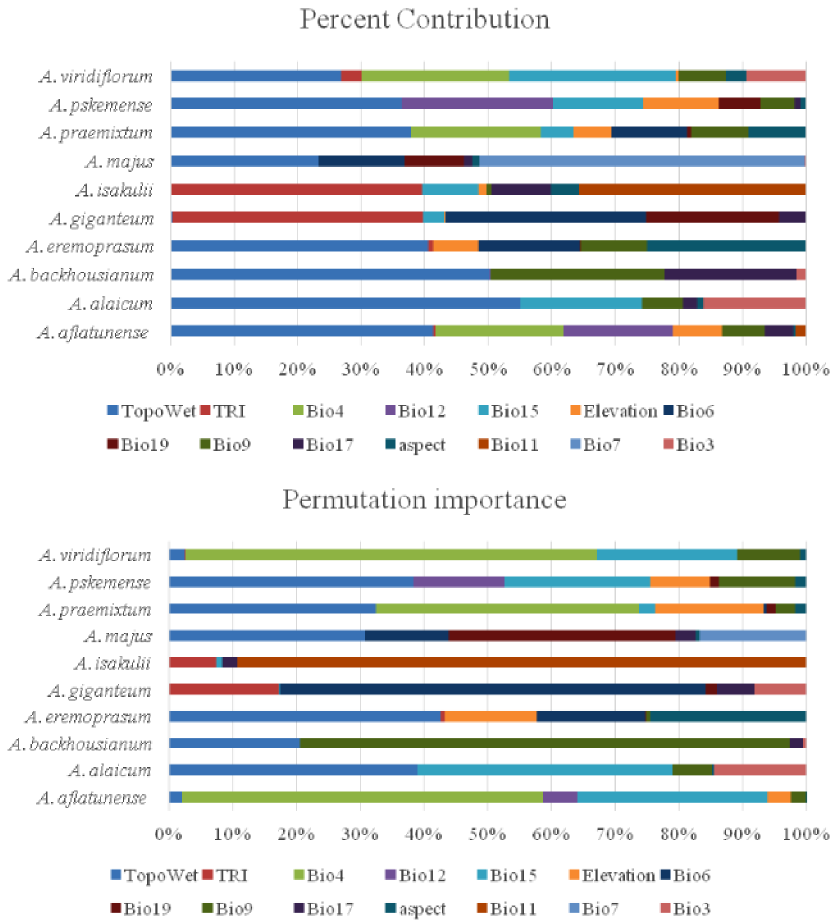


**Figure 5**. Percent contribution and permutation importance units for Maxent models of ten *Allium* species under current conditions.

According to the MaxEnt model, *A. viridiflorum* currently has approximately 239,143 km² of suitable habitat (low, midde and highly suitable) in Central Asia, accounting for 5.22% of the region's total land area.. Highly suitable habitats are distributed across the Turkistan, Fergana, Alai, and Kyrgyz ranges, as well as the Pamir Mountains. Moderately suitable habitats cover 59,192 km² (1.29%), while low-suitability habitats occupy 145,742 km² (3.18%). There are also small pockets of highly suitable habitats along the eastern part of Afghanistan and in the southwestern part of Turkmenistan, particularly in the Kopetdag Range. In the future, the area of high-suitability habitats decreases to 0.72%, and the moderately suitable area contracts slightly to 1.19%. Low-suitability habitats increase to 3.05%. This reflects a potential decrease in the optimal conditions for *A. viridiflorum* and an expansion of less suitable habitats under changing environmental conditions. Suitable habitats for *A. viridiflorum* are predominantly found on lithosols and calcic xerosols (Fig. 7).

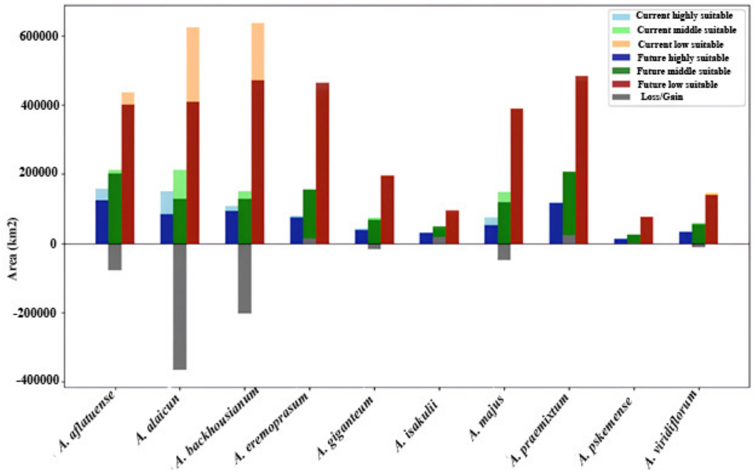


**Figure 6**. Changes in the suitable habitats of ten *Allium* species under present and future climatic conditions.

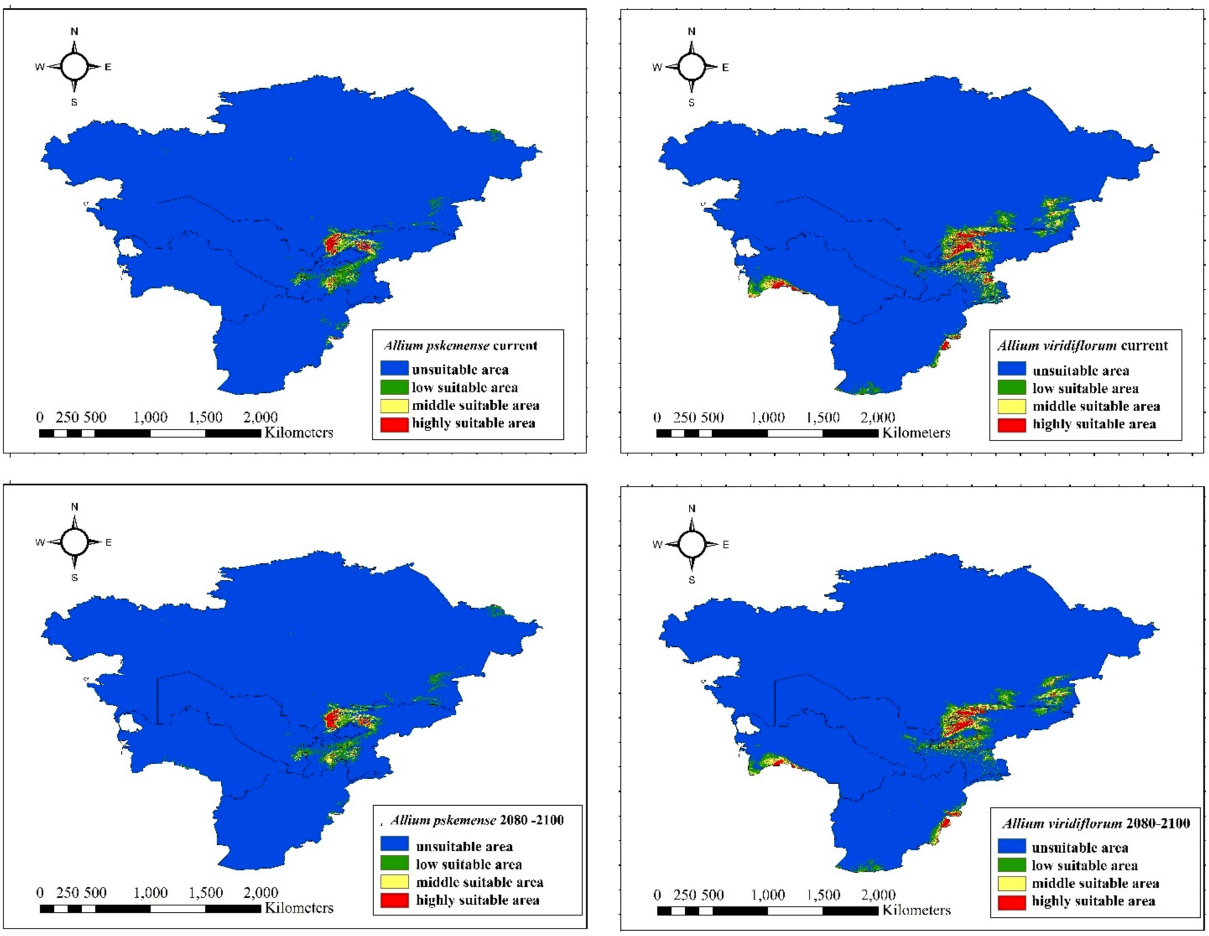


**Figure 7.** Predicted potentially suitable distribution areas of *A. pskemense* and *A. viridiflorum* in Central Asia and Afghanistan at current (above) and 2080-2100s (below).

According to MaxEnt modeling, the current suitable habitat (low, midde and highly suitable) for *A. majus* encompasses approximately 609,161 km², representing 13.3% of Central Asia's total land area.. Highly suitable habitats are located in the Chatkal Range, Gissar Range, Turkistan Mountains, and Hindu Kush. Moderately suitable habitats cover 148,573 km² (3.24%), while low-suitability habitats span 384,995 km² (8.4%). There is also a small number of highly suitable habitats in the southwestern part of Turkmenistan. Under future environmental conditions, high-suitability habitats increase slightly to 1.14%, and moderately suitable habitats grow to 2.58%, suggesting a slight improvement in conditions for *A. majus*. However, low-suitability habitats also increase to 8.51%. The soils most suitable for *A. majus* include calcic xerosols and lithosols (Fig. 8).

According to MaxEnt modeling, the current suitable habitat for *A. praemixtum* spans approximately 786,225 km², representing 17.17% of Central Asia's total land area. The most highly suitable habitats are found in the Fergana Range, Alai Range, Kyrgyz Range, Turkistan Range, Zarafshan Range, and Alai Mountains. The moderately suitable habitats cover 201,947 km² (4.41%), and low-suitability habitats cover 469,972 km² (10.26%). Additional patches of suitable habitat exist along the eastern part of Afghanistan and in southwestern Turkmenistan. Future projections show an increase in moderately suitable habitats to 4.54%, and low-suitability habitats expand to 10.57%. The high-suitability areas, however, increase to 2.57%. This indicates a shift toward more marginal habitats under changing environmental conditions. Lithosols and calcic xerosols are the dominant soil types in the most suitable areas for *A. praemixtum* (Fig. 7).

According to the MaxEnt model, *A. giganteum* currently has approximately 317,958 km² of suitable habitat (low, midde and highly suitable) in Central Asia, representing 6.94% of the region's total land area.. Highly suitable areas are located in the Gissar Range, Tian Shan, and Hindu Kush. Moderately suitable habitats cover 75,162 km² (1.64%), and low-suitability habitats span 198,936 km² (4.34%). A few highly suitable habitats are found in the eastern part of Afghanistan and southwestern Turkmenistan. Under future conditions, the high-suitability habitats decrease to 0.84%, and moderately suitable habitats to 1.48%, while low-suitability habitats increase to 4.23%. This pattern indicates a reduction in optimal conditions for *A. giganteum*, with more marginal habitats being suitable in the future. The primary soil types found in suitable habitats include lithosols and calcic xerosols (Fig. 9).

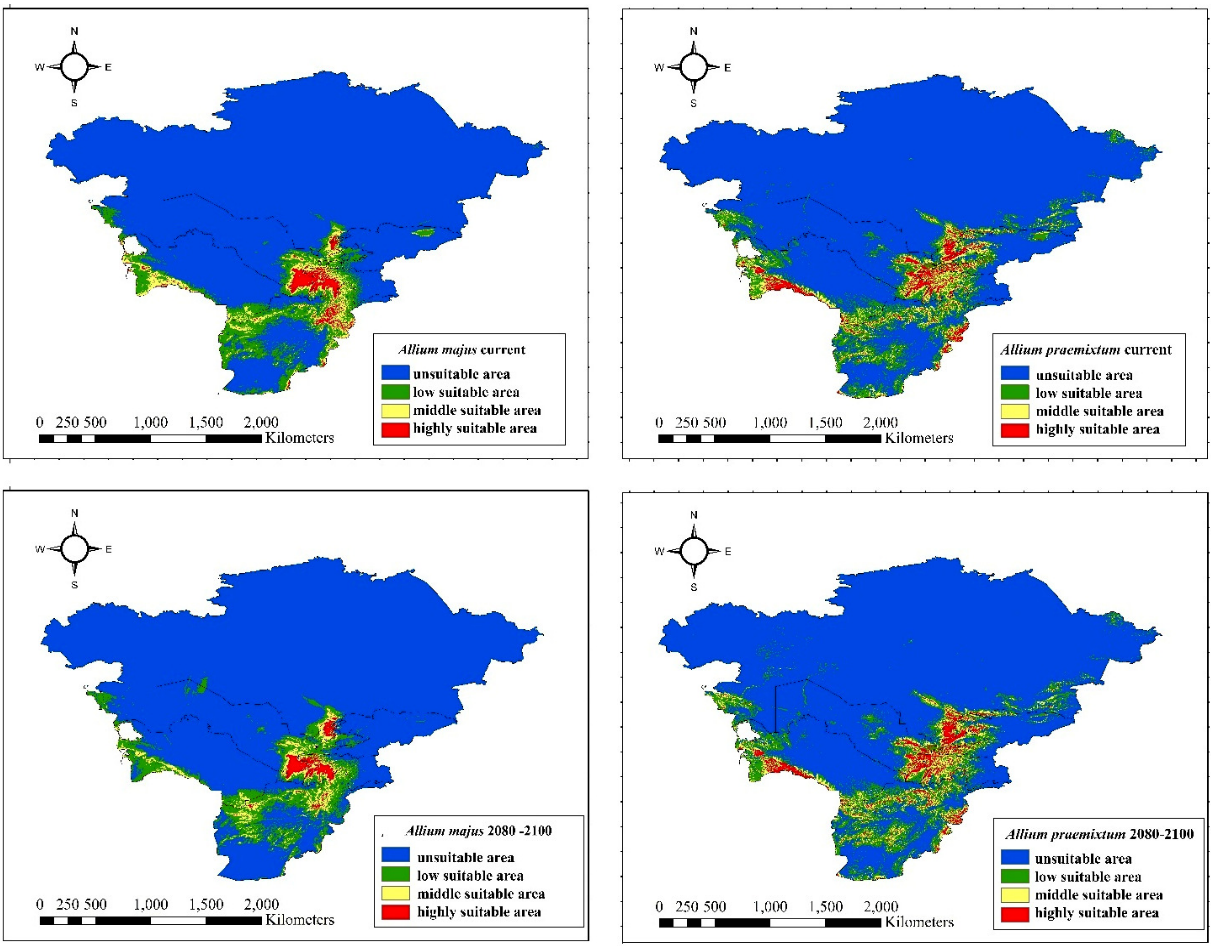


**Figure 8.** Predicted potentially suitable distribution areas of *A. majus* and *A. praemixtum* in Central Asia and Afghanistan at current (above) and 2080-2100s (below).

According to MaxEnt modeling, the current suitable habitat (low, midde and highly suitable) for *A. isakulii* spans approximately 155,671 km², accounting for 3.39% of Central Asia's total land area. Highly suitable habitats are distributed across the Zarafshan, and Turkistan Mountains. The moderately suitable areas cover 41,203 km² (0.899%), and low-suitability areas occupy 86,741 km² (1.89%). Under future climate scenarios, the areas of high-suitability habitats decrease to 0.66%, while moderately suitable areas increase to 1.06%, and low-suitability habitats expand to 2.05%. Lithosols and calcic xerosols are the dominant soil types in areas where *A. isakulii* is most suitable (Fig. 9).

According to MaxEnt modeling, the suitable habitat (low, midde and highly suitable) for *A. backhousianum* currently covers approximately 896,607 km², representing 19.58% of Central Asia's total land area. Highly suitable habitats are found in the Fergana, Alai, Kyrgyz, Turkistan, Zarafshan, and Hindu Kush ranges. Moderately suitable areas cover 150,380 km² (3.28%), and low-suitability areas span 637,712 km² (13.92%). There are small pockets of suitable habitats along the southwestern part of Turkmenistan and southeastern Kazakhstan. In the future, high-suitability habitats decrease to 2.02%, moderately suitable habitats decrease to 2.81%, and low-suitability habitats expand to 10.27%. The primary soil type in the most suitable areas is lithosols (Fig. 10).

According to MaxEnt modeling, the current suitable habitat (low, midde and highly suitable) for A. eremoprasum spans approximately 680,508 km², accounting for 14.86% of Central Asia's total land area. Highly suitable areas are concentrated in the Turkistan and Tian Shan mountains. Moderately suitable habitats cover 157,081 km² (3.43%), and low-suitability habitats occupy 443,939 km² (9.69%). Small patches of suitable habitat are located in southwestern Turkmenistan and parts of Kazakhstan. In future conditions, high-suitability habitats decrease to 1.64%, while moderately suitable habitats increase to 3.37%, and low-suitability habitats grow to 10.14%. The primary soil types in the suitable habitats for *A. eremoprasum* are lithosols and calcic xerosols (Fig. 10).

According to MaxEnt modeling, the suitable habitat (low, midde and highly suitable) for *A. aflatunense* spans approximately 806,981 km², accounting for 17.62% of Central Asia's total land area. Highly suitable areas are found in the Turkistan, Zarafshan, and Chatkal ranges, as well as in the Pamir and Hindu Kush mountains. Moderately suitable habitats cover 213,232 km² (4.65%), and low-suitability habitats occupy 435,391 km² (9.5%). Under future conditions,

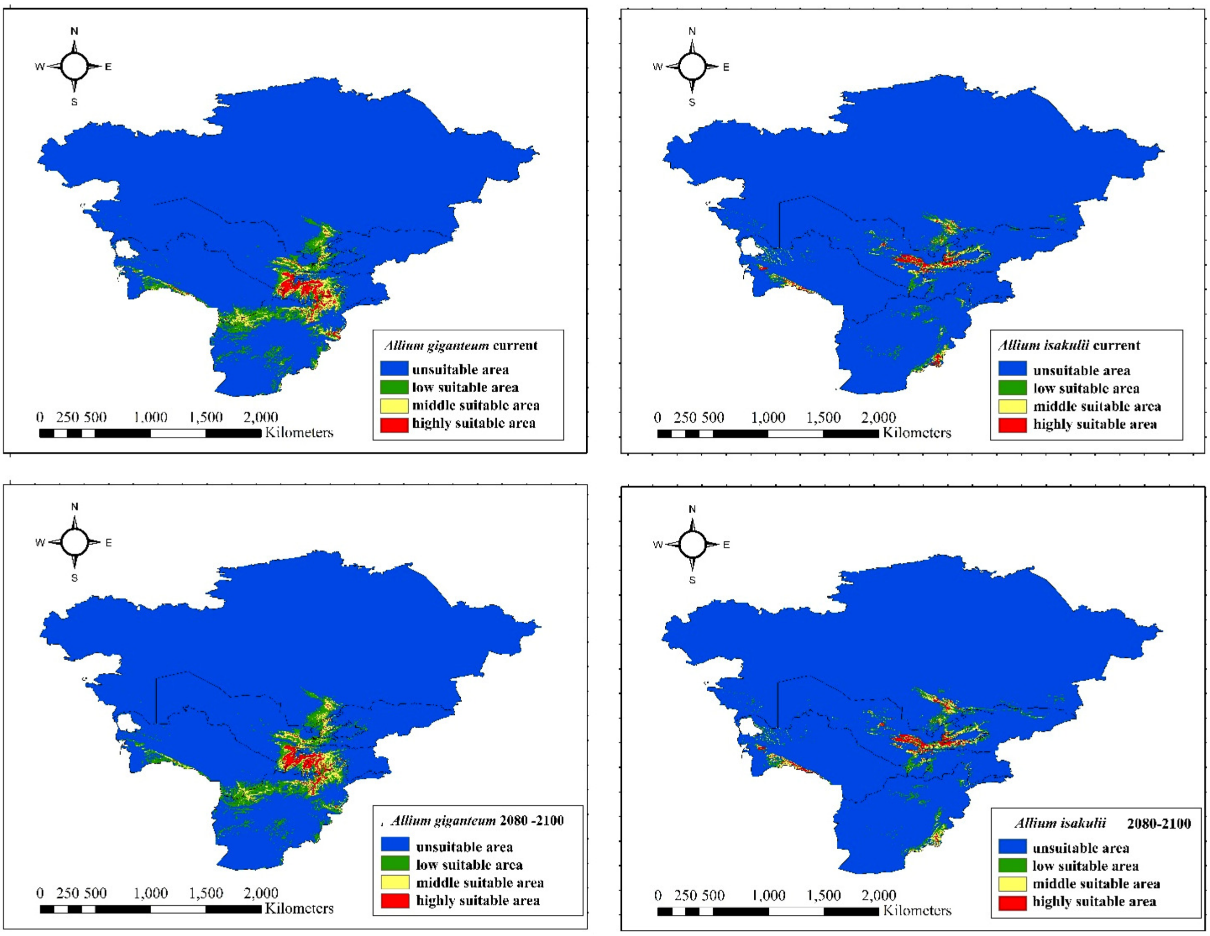


**Figure 9.** Predicted potentially suitable distribution areas of *A. giganteum and A. isakulii* in Central Asia and Afghanistan at current (above) and 2080-2100s (below).

high-suitability habitats decrease to 2.71%, while moderately suitable habitats increase to 4.42%, and low-suitability habitats decrease to 8.77%. The dominant soil types for *A. aflatunense* in the most suitable areas are lithosols (Fig. 11).

According to MaxEnt modeling, the suitable habitat (low, midde and highly suitable) for A. alaicum currently spans approximately 987,381 km², representing 21.56% of Central Asia's total land area . Highly suitable areas are located in the Fergana, Alai, Kyrgyz, Turkistan, and Alai Mountains. Moderately suitable habitats cover 213,104 km² (4.65%), and low-suitability habitats cover 624,654 km² (13.64%). In the future, high-suitability habitats decrease to 1.829%, moderately suitable habitats decrease to 2.8%, and low-suitability habitats increase to 8.93%. Lithosols are the predominant soil type in the suitable habitats for *A. alaicum* (Fig. 11).

## DISCUSSION

In this study, we assessed the impact of climate change on the potential distribution of ten threatened *Allium* species (*A. isakulii*, *A. giganteum*, *A. aflatunense*, *A. majus*, *A. alaicum*, *A. backhousianum*, *A. eremoprasum*, *A. pskemense*, *A. viridiflorum*, and *A. praemixtum*) in Central Asia. Our results suggest that, with the exception of *A. eremoprasum*, *A. isakulii*, *A. praemixtum*, and *A. pskemense*, the potentially suitable habitats for most of these species are expected to decline under future climate scenarios. This decline aligns with findings from similar studies conducted in other parts of the world, where climate change has been identified as a significant threat to the distribution of endemic and rare plant species [9]. For instance, Khajoei-Nasab *et al.* [17] observed a similar decrease in suitable habitats for many endemic *Allium* species in Iran, underlining the vulnerability of these plants to shifting climatic conditions. These trends reflect broader global patterns, wherein climate change is increasingly recognized as a key driver of biodiversity loss [31].

In our analysis, we identified several environmental variables that play a crucial role in shaping the habitat suitability of the studied *Allium* species. The Topographic Wetness Index (TopoWet), Terrain Roughness Index (TRI), Minimum Temperature of the Coldest Month (Bio6), and Precipitation of the Coldest Quarter (Bio19) were the most influential factors. These variables were found to significantly impact the suitability of habitats for the studied species.

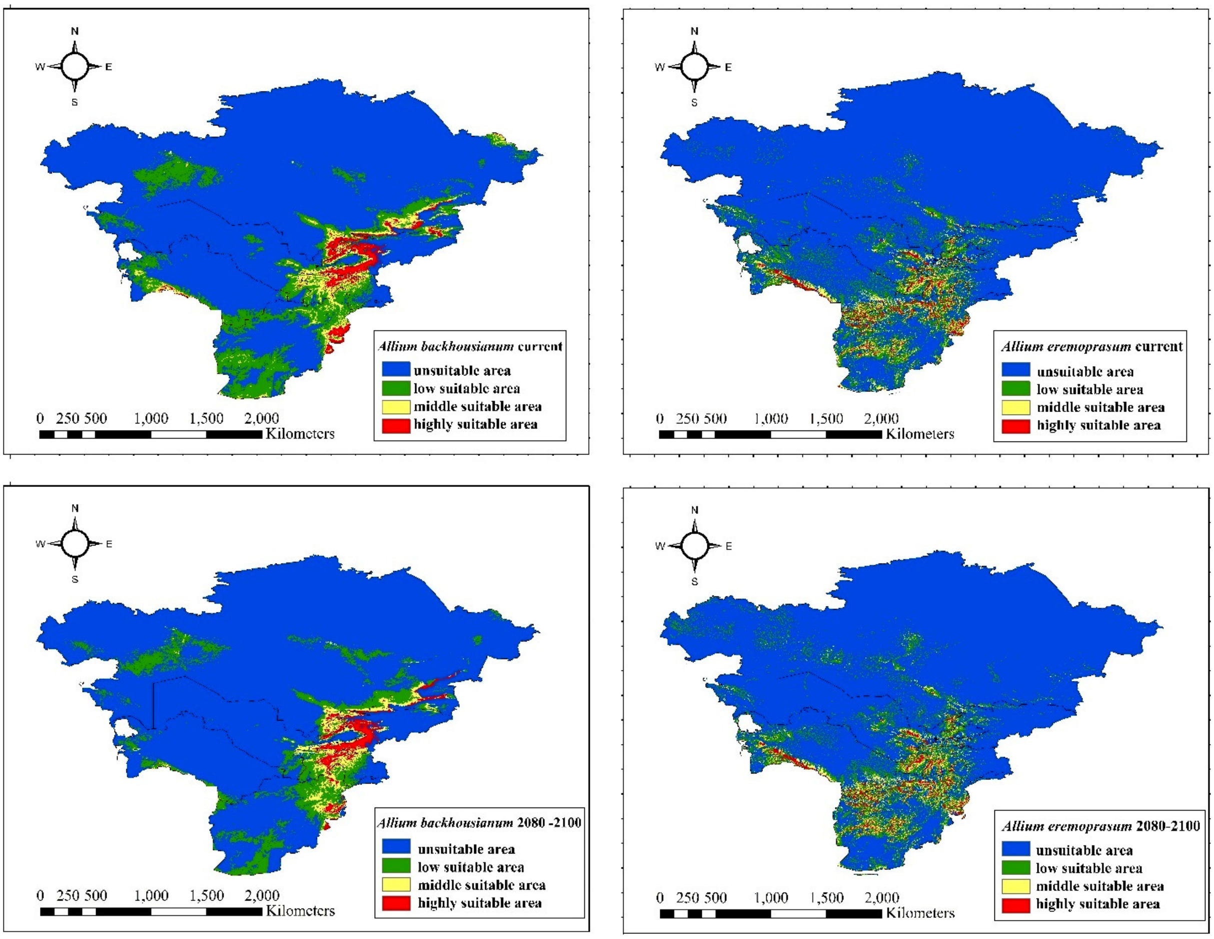


**Figure 10.** Predicted potentially suitable distribution areas of *A. backhousianum* and *A. eremoprasum* in Central Asia and Afghanistan at current (above) and 2080-2100s (below).

Interestingly, studies on *Allium* species in Iran highlighted different factors, such as the Annual Mean Temperature (Bio1), Temperature Annual Range (Bio7), and Annual Precipitation (Bio12), as critical determinants of species distribution [27]. The integration of both climate and topographic variables in ecological niche models has proven effective in predicting species distributions and identifying areas of high conservation value [7, 32]. Our use of ENVIREM datasets, which incorporate expanded bioclimatic and topographic variables, further strengthened the accuracy of the species distribution models. These datasets have been shown to enhance the performance of ecological niche modeling tools, improving predictions of species' habitat preferences [3]. This methodology allowed us to pinpoint the environmental variables that most substantially affect habitat suitability for *Allium* species in Central Asia, providing more precise predictions for future conservation strategies.

Regarding *A. pskemense*, a rare endemic species restricted to the western Tien-Shan, our MaxEnt model predicts that the species' protected areas, such as the Ugam-Chatkal National Park and the Chatkal Biosphere State Reserve, will remain suitable under future climate conditions. However, the overall extent of suitable habitat is expected to slightly decrease. This finding is consistent with Khassanov [15], who highlighted the species' vulnerability due to anthropogenic threats, including human collection and poor seed germination. The projected decline in suitable habitats, compounded by these threats, underscores the need for additional conservation efforts, such as habitat restoration and enhanced protection of seed banks, to secure the species' survival [23]. Abduraimov *et al.* [1] also shed light on the demographic health of *A. pskemense* populations, noting that cattle grazing and germination conditions significantly affect ontogenetic development. The absence of senile age groups in some cenopopulations, linked to specific ecological conditions and the species' biology, further complicates its conservation. These findings suggest that efforts should focus not only on habitat protection but also on improving habitat quality, particularly by minimizing disturbances like grazing. Additionally, some populations were predominantly young, with a high restoration index, which signals successful seed replenishment but an imbalanced population structure. To enhance the species' long-term survival, conservation strategies should focus on supporting all life stages, ensuring the sustainability of both generative and senile individuals. Combining habitat expansion, grazing management, and seed bank protection with habitat restoration could help mitigate the impacts of climate change and anthropogenic threats.

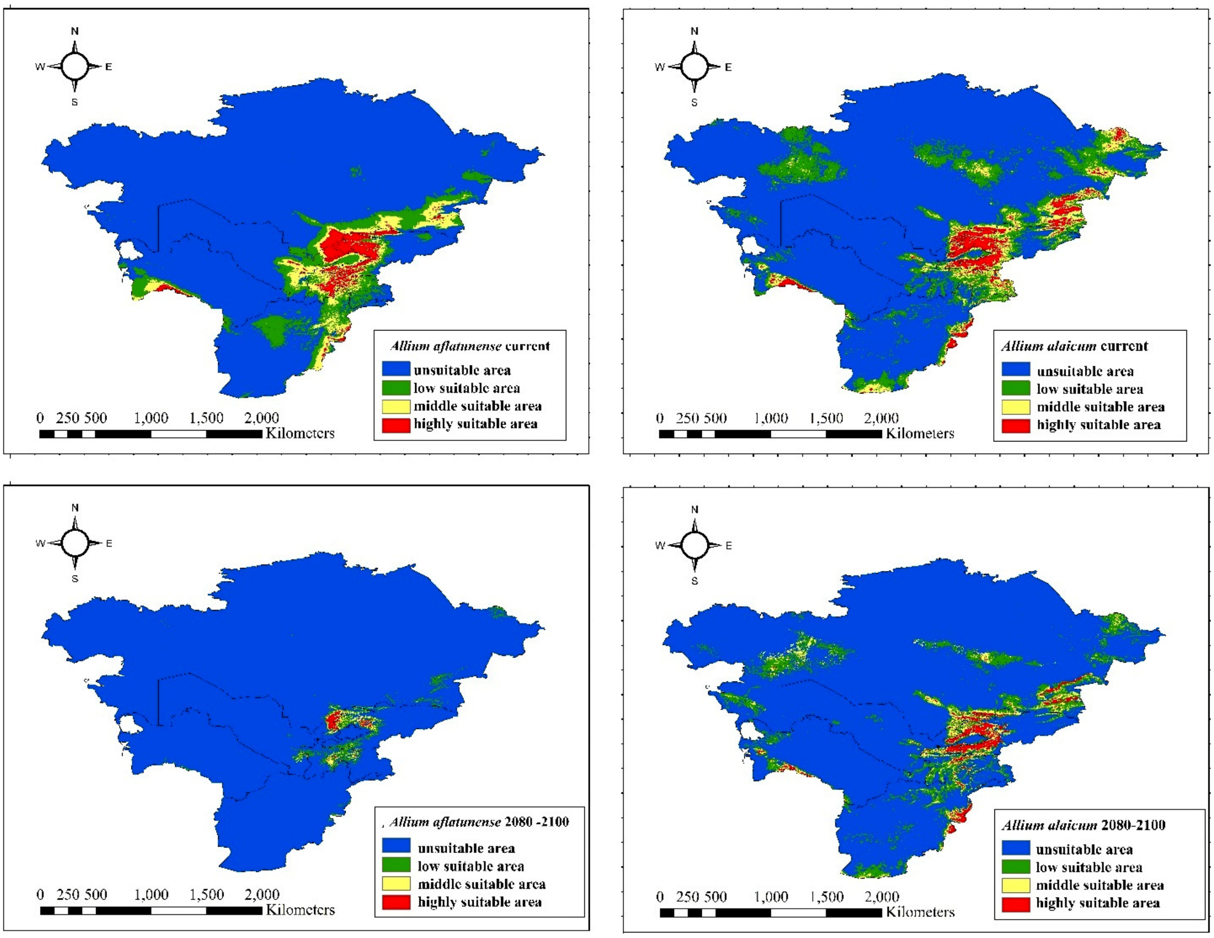


**Figure 11.** Predicted potentially suitable distribution areas of *A. aflatunense and A. alaicum* in Central Asia and Afghanistan at current (above) and 2080-2100s (below).

For *A. viridiflorum*, an endemic species to the Chatkal Range that is not currently protected in any state reserve, our analysis suggests that the Chatkal and Ugam-Chatkal State Nature Reserves could serve as potential refugia under future climate conditions. However, pasturing remains a significant threat, as noted by Khassanov [15]. Climate-induced habitat loss may exacerbate existing pressures, leading to population declines. Thus, expanding these protected areas and limiting grazing within reserves would be crucial to maintaining *A. viridiflorum* populations.

*A. majus*, found in the western Pamir-Alay, is currently protected in the Hissar and Kitab State Reserves. Our findings indicate that additional reserves, such as Surkhan State Nature Reserve and the Nurata, Chatkal, and Ugam-Chatkal State Nature Reserves, could offer suitable habitats for the species. However, significant threats from pasturing and bulb collection may intensify with climate change [13]. Expanding conservation measures, such as restricting human access to key habitats and implementing better land management strategies, is essential [3]. Saidmuratov *et al.* [29] emphasized that the species faces pressures from bulb collection and grazing, and its reproduction primarily occurs vegetatively, which may limit genetic diversity. To ensure *A. majus*' long-term survival, conservation efforts should focus on both seed and vegetative reproduction conditions, along with habitat restoration and minimizing human disturbances.

*A. praemixtum*, a rare endemic species in the western Tien-Shan and Nuratau Mountains, is protected in the Nuratau State Reserve. Our modeling results suggest that additional protected areas, such as Hissar State Reserve, Surkhan State Reserve, and the Chatkal and Ugam-Chatkal State Reserves, could provide support for the species. Local collection remains a significant threat [15], and to mitigate the effects of climate change, strengthening enforcement against illegal collection and raising public awareness of its conservation status is critical [33, 35]. Saribaeva *et al.* [30] highlighted the incomplete cenopopulations of *A. praemixtum*, with a lack of pregenerative individuals due to grazing. They noted that high grazing pressure shifts the ontogenetic spectrum to be centered and bimodal, limiting the species' life cycle. Despite its high seed productivity, the species faces risks from overgrazing and uncontrolled harvesting. As Saribaeva *et al.* [30] suggest, stricter protection, including limiting grazing and harvesting, and habitat restoration are crucial to prevent local extinction.

*A. giganteum*, endemic to the southern Pamir-Alay and Kopetdag, is currently protected in the Surkhan State Nature Reserve. Our results suggest that the Hissar State Reserve could also provide suitable habitat for the species. However, threats from low seed germination and pasturing [15] may be compounded by the potential reduction in suitable habitats due to climate change. Ongoing monitoring of population dynamics and habitat quality is essential to ensure the persistence of *A. giganteum* under changing environmental conditions [18].

For *A. isakulii*, found in the western Tien-Shan and Pamir-Alay, and currently protected in the Nuratau State Reserve, our results suggest that the Aktau-Tamdy State Nature Reserve could also support the species under future climate conditions. The species faces threats from pasturing and low seed germination [15], which may be exacerbated by climate-induced habitat shifts. Long-term conservation of *A. isakulii* will require both in situ conservation and the establishment of seed banks to safeguard its genetic diversity [25].

*A. backhousianum*, native to the Fergana and Alay mountain regions, is not currently protected in any state reserve. Our analysis suggests that the Chatkal and Ugam-Chatkal State Nature Reserves could serve as potential refugia for this species, especially given the threat of poor seed germination [15]. Climate change may limit the availability of suitable habitats, making conservation efforts in these areas a priority.

*A. aflatuense*, endemic to the western Tien-Shan, it is protected in the Chatkal Biosphere State Reserve. Our analysis suggests that the Ugam-Chatkal and Nurata State Nature Reserves could also support this species under future climate conditions. Local collection for food and medicinal purposes poses a significant threat [15], and expanding conservation efforts, particularly community-based management strategies, will be essential to address these pressures.

*A. alaicum*, found in the Alay range, *A. alaicum* is not currently protected in any state reserve. Our results suggest that the Chatkal and Ugam-Chatkal State Nature Reserves could serve as potential refuges under future climate conditions. Pasturing is a significant threat to this species [15]. As climate change is likely to increase grazing pressure in some areas, it is vital to implement adaptive management strategies, such as rotational grazing and improved pasture management, to mitigate these threats.

Finally, *A. eremoprasum*, found in the western Pamir-Alay and not currently protected in any state reserve, may find suitable habitats in the Hissar State Reserve under future climate scenarios. However, the species faces significant threats from quarrying and mining activities [15], which could be exacerbated by climate-induced habitat loss. Active restoration of degraded habitats and stricter regulations on industrial activities are essential to protect *A. eremoprasum*.

In terms of soil data, our analysis revealed that lithosols (I) and calcic xerosols (Xk) are the most congruent soil types with the highly suitable areas for the studied *Allium* species. This finding is consistent with the ecological preferences of many *Allium* species, which tend to thrive in rocky, well-drained soils [16]. Identifying these soil types as suitable for *Allium* species provides valuable information for future conservation efforts, especially in selecting areas for *in situ* and *ex situ* conservation.

Overall, the results of this study provide a scientific foundation for the conservation of *Allium* species in Central Asia. The identification of key environmental variables and the modeling of suitable habitats under future climate scenarios will inform the establishment of protected areas and the development of targeted conservation strategies. The integration of MaxEnt modeling with ENVIREM datasets has proven to be an effective tool in predicting species distributions and identifying areas of high conservation value [7, 32]. Our findings highlight the importance of considering both climatic and topographic factors in species distribution modeling, as these variables significantly influence habitat suitability for *Allium* species.

This study highlights the significant impact of climate change on the future distribution of ten threatened *Allium* species in Central Asia. Using MaxEnt modeling and ENVIREM datasets, we have provided a comprehensive analysis of current and future habitat suitability for these species, taking into account critical environmental variables such as topographic wetness, terrain roughness, temperature, and precipitation patterns. Our findings show that, with the exception of *A. eremoprasum*, *A. isakulii*, *A. praemixtum*, and *A. pskemense*, most of the species are expected to experience a decline in highly suitable habitats under future climate scenarios, shifting towards more marginal areas. These changes are compounded by ongoing anthropogenic pressures, such as overgrazing, bulb collection, and habitat degradation, which further threaten the survival of these endemic species.

The study underscores the importance of incorporating both climatic and topographic factors in conservation planning. The identification of key environmental variables and soil types that support these species provides valuable insights for designing targeted conservation strategies. These strategies should include habitat restoration, expansion of protected areas, and the implementation of community-based management practices to mitigate the effects of climate change and human interference. Additionally, proactive efforts to safeguard seed banks, control grazing, and reduce habitat degradation will be crucial for ensuring the long-term survival of these species in the face of a changing climate.

Overall, this research provides a scientific foundation for the conservation of Central Asia's *Allium* species, emphasizing the need for a multi-faceted approach to preserve biodiversity and safeguard these valuable plant species in the region.

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**Conflict of interest.** There is no actual or potential conflict of interest in relation to this article.

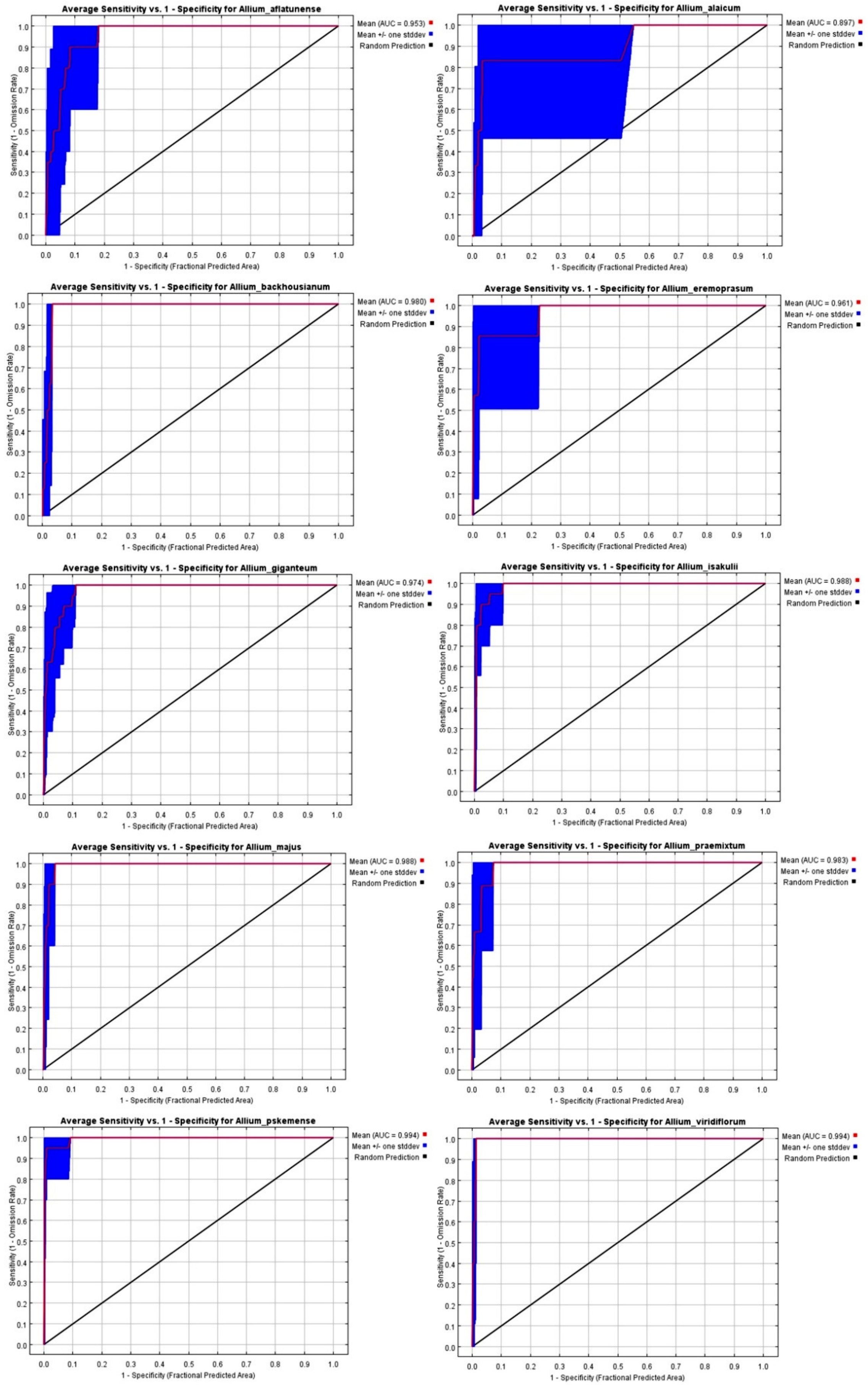
## SUPLEMENTARY DATA

**Sapplementary Tabe 1.** Bioclimatic variables' description used in the study.

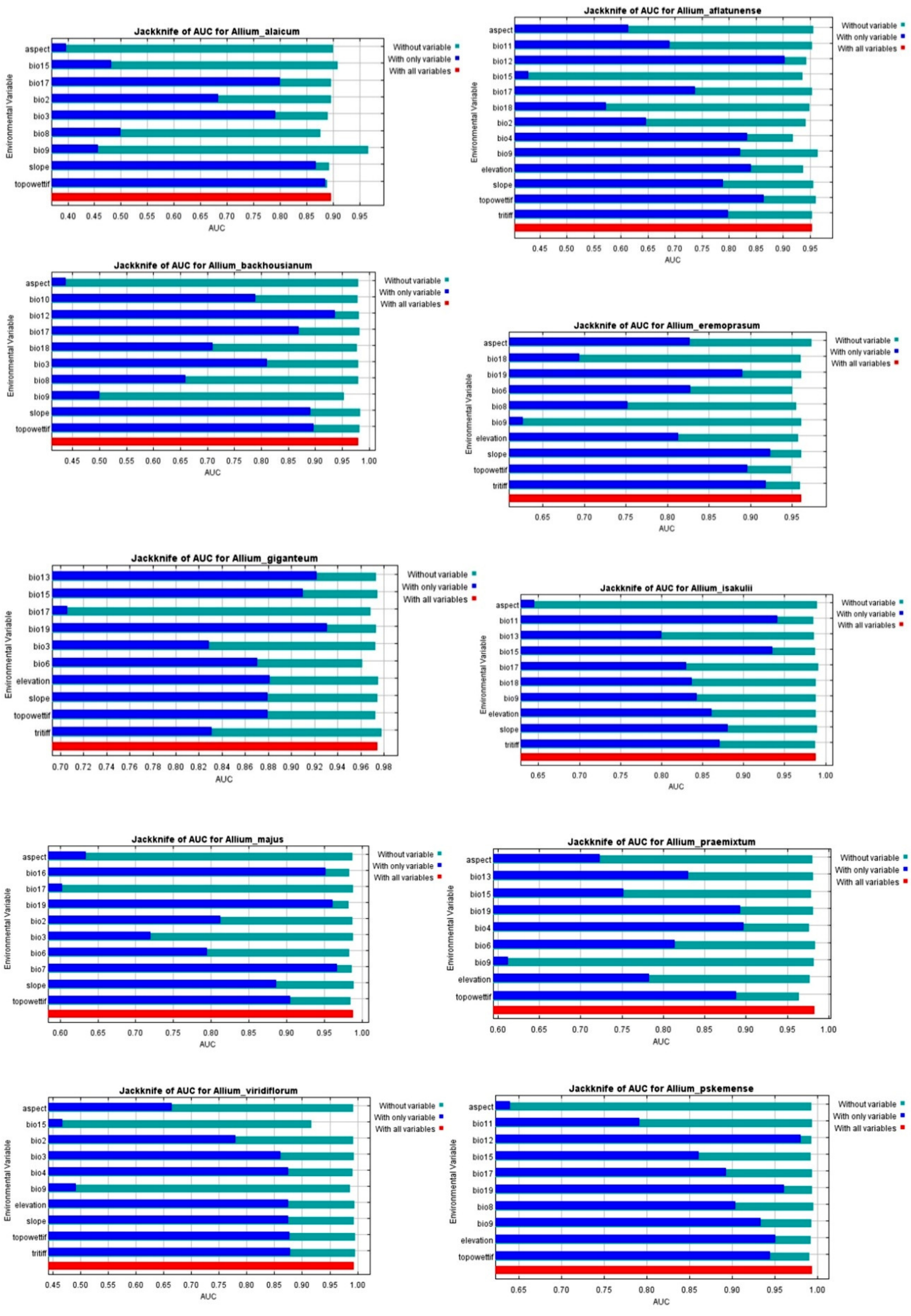
| Data Source and Category | Environmental Variable | Description | Unit |
|---|---|---|---|
| Worldclim Bioclimatic data | Bio1 | Annual mean temperature | °C |
| | Bio2 | Mean diurnal range (mean of monthly (max temp – min temp)) | °C |
| | Bio3 | Isothermality (Bio2/Bio7) (×100) | - |
| | Bio4 | Temperature seasonality (standard deviation ×100) | - |
| | Bio5 | Maximum temperature of the warmest month | °C |
| | Bio6 | Minimum temperature of the coldest month | °C |
| | Bio7 | Temperature annual range (Bio5−Bio6) | °C |
| | Bio8 | Mean temperature of the wettest quarter | °C |
| | Bio9 | Mean temperature of the driest quarter | °C |
| | Bio10 | Mean temperature of the warmest quarter | °C |
| | Bio11 | Mean temperature of the coldest quarter | °C |
| | Bio12 | Annual precipitation | mm |
| | Bio13 | Precipitation of the wettest month | mm |
| | Bio14 | Precipitation of the driest month | mm |
| | Bio15 | Precipitation seasonality (coefficient of variation) | - |
| | Bio16 | Precipitation of the wettest quarter | mm |
| | Bio17 | Precipitation of the driest quarter | mm |
| | Bio18 | Precipitation of the warmest quarter | mm |
| | Bio19 | Precipitation of the coldest quarter | mm |
| ENVIREM dataset | TRI | Terrain roughness index | - |
| | TopoWet | SAGA-GIS topographic wetness index | - |
| Worldclim Bioclimatic data | Elevation | Elevation | m |
| | Slope | Slope | degree |
| | Aspect | Aspect | degree |

**Sublementary Table 2.** Changes in the suitable habitats of ten *Allium* species under present and future climatic conditions in km$^2$.

| | | Current scenario (km$^2$) | | | Future scenario (2080-2100) (km$^2$) | | | Loss/Gain (km$^2$) |
|---|---|---|---|---|---|---|---|---|
| No. | Species name | highly suitable | middle suitable | low suitable | highly suitable | middle suitable | low suitable | Loss / Gain of total suitable area |
| 1 | *Allium aflatunense* B.Fedtsch. | 158358 | 213232 | 435391 | 124313 | 202694 | 401702 | -78272 |
| 2 | *Allium alaicum* Vved. | 149623 | 213104 | 624654 | 83759 | 128546 | 409013 | -366063 |
| 3 | *Allium backhousianum* Regel | 108515 | 150380 | 637712 | 92938 | 129095 | 470692.5 | -203881.5 |
| 4 | *Allium eremoprasum* Vved. | 79488 | 157081 | 443939 | 75423 | 154555 | 464305.5 | 13775.5 |
| 5 | *Allium giganteum* Regel | 43860 | 75162 | 198936 | 38521 | 67846 | 194074 | -17517 |
| 6 | *Allium isakulii* R.M.Fritsch & F.O.Khass. | 27727 | 41203 | 86741 | 30301 | 48574 | 94181 | 17385 |
| 7 | *Allium majus* Vved. | 75593 | 148573 | 384995 | 52496 | 118479 | 389880 | -48306 |
| 8 | *Allium praemixtum* Vved. | 114306 | 201947 | 469972 | 117845 | 208045 | 484222 | 23887 |
| 9 | *Allium pskemense* B.Fedtsch. | 14599 | 25050 | 75069 | 12864 | 25411 | 76668 | 225 |
| 10 | *Allium viridiflorum* Pobed. | 34209 | 59192 | 145742 | 33011 | 54564 | 140017 | -11551 |




**Supplementary Figure 1**. ROC curve and AUC values for the reconstructed model for ten *Allium* species




**Supplementary Figure 2**. Jackknife of AUC tests for climatic factors in the current potential distribution model of ten *Allium* species

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