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Predicting the impact of climate change on *Ranunculus aucheri* (Ranunculaceae) using species distribution modeling

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ABSTRACT
The climate phenomenon is the biggest environmental challenge currently facing the world, impacting all ecosystems, including the distribution of plant species. This research aims to predict the climatic effects on the spatial distribution of the *R. aucheri* under the scenarios of the RCP8.5 (optimistic) and RCP2.6 (pessimistic) models for two-time scales: 2050 and 2080. It utilizes five species distribution modeling methods, including generalized linear models, classification tree analysis, artificial neural networks, generalized additive models, and random forests, within a consensus framework in R software. The results have been analysed and compared. The overall conclusion from these reports is that the most significant variables affecting the distribution of this species, based on the modeling results, are temperature, soil depth, precipitation, and sand content, in that order. Model evaluation indicates that this species will experience a reduction in its distribution area due to climate change and will also be introduced to other areas, with the least change being a 28.35% reduction in range under the optimistic scenario by 2050, and the most significant change being a 67.12% reduction in range under the pessimistic scenario by 2080. The results of this study can be utilized in conservation and corrective programs for the *R.aucheri*.

Keywords: Alborz, BIOMOD2, Habitat changes, Habitat prediction, Zagros.
Article type: Research Article.

INTRODUCTION
The biotic potential of a species and the environmental factors affecting the distribution and geographical expansion of species are altered by climate change. Temperature and precipitation, along with biotic interactions, are the primary factors influencing species distribution (Woodward *et al.* 1987; Abolmaali *et al.* 2018). These factors can be significantly affected by global warming, leading to population harm and, consequently, the risk of extinction or endangerment of species. Climate change is the biggest environmental challenge currently facing the world. It is predicted that this phenomenon will impact all aspects of human life and affect all ecosystems globally in ecological, geological, meteorological, and other respects (Loarie *et al.* 2008; Cuena-Lombrana *et al.* 2018). The impacts of human activity on climate system changes are evident, with greenhouse gas emissions recently reaching their highest levels in history. Climate changes have had widespread effects on human and natural systems. The warming of the climate system since the 1950s is clearly observable, and many of the changes seen over the past decades are unprecedented. The resilience of endemic species and those dependent on border areas (cool and moist regions) to these changes will be much more challenging, and the consequences will be far more severe. Because these groups of species have adapted to very specific and delicate living and habitat conditions, with very limited opportunities for distribution (Bellard *et al.* 2012). To protect plant species and assess their threat levels and management, it is essential to predict the effects of climate on their distribution

(Ghahremaninejad *et al.* 2021). Climate conditions and how changes in these conditions affect plant distribution can be demonstrated and defined using the range and geographical scope of plant distribution. Today, employing new statistical algorithms and techniques instead of traditional, time-consuming methods is a fast and powerful approach for predicting species distribution and presence, actual distribution, potential vegetation cover, and creating predictive maps of species distribution under different environmental data. These environmental data are often climatic data (Franklin 2013). Species Distribution Modeling (SDM), Environmental (or Ecological) Niche Modeling (ENM), Predictive Habitat Distribution Modeling, and Range Mapping are terms used to describe these methods. Based on Franklin (2013) studies, SDMs have evolved from a few papers annually in the 1980s to nearly a thousand published annually at present, reflecting their importance in conservation efforts. In species distribution models, occurrence and non-occurrence data of species, along with the corresponding environmental conditions of the study area, are utilized to model and express the species' needs. These conditions are then explored across the entire area to generate potential habitat maps for the species. This relationship can be used to develop a predictive model of species distribution under climate change scenarios (Pearson & Dawson 2003). Recently the review by Babanezhad and Naqinezhad (2024) positioned species distribution models as pivotal in the quest for effective plant conservation strategies, particularly within the distinctive ecological context of Iran. Hosseini *et al.* (2024) examined the profound effects of climate change on biodiversity and species distribution, specifically focusing on two thyme species, *Thymus daenensis* and *Thymus kotschyanus*, in Iran. The Ranunculeae tribe diversified between the late Eocene and late Miocene. During this period, major oceanic barriers already separated continents, and dispersal is considered the primary explanation for the tribe's current distribution. In the Southern Hemisphere, intercontinental movements likely occurred either through land bridges or long-distance dispersal events (Emadzade & Hörandl 2011). *Ranunculus* species thrive in diverse environments, ranging from wet to dry and lowland to alpine zones, with various morphological adaptations for different habitats. Mountain regions host high endemism, boosting species diversity, while lower altitudes are dominated by widespread species. The genus also exhibits varying levels of polyploidy, occasionally linked to apomixis (Hörandl *et al.* 2005). One of the rare *Ranunculus* species in mountainous areas is the *Ranunculus aucheri* Boiss., which has been proposed as a complex of the species *R. elburzensis* Boiss. and *R. pichleri* Freyn. In the literature, the latter two species are synonymized with *Ranunculus aucheri* (Iranshahr *et al.* 1992; Pakravan & Sharifnia 2022; Pakravan & Assadi 2024; Pakravan *et al.* 2024). *R. aucheri* is a perennial herb with tuberous roots that allow it to withstand drought and low water conditions in high mountain areas. This plant, which is distributed in the mountainous regions of Alborz and Zagros, is endemic and endangered (Bidar Lord *et al.* 2016). *Ranunculs* species due to presence of ranunculin alkaloid, saponins, flavonoids, tannins and phenols, in the cells are very useful in traditional medicines for swell-reducing, malaria, arthritis, ulcer disease and asthma. Also, it is known for anticancer, analgesic, cardiovascular and antimicrobial effects (Aslam *et al.* 2012). Therefore, to protect and manage its distribution areas, it is necessary to make management decisions to understand the potential impacts of climate change on species distribution and to mitigate the harmful effects of climate change on biodiversity (Pressey *et al.* 2007). Examining the distribution of sensitive species as indicators for assessing ecosystem conditions can provide valuable information for managers and specialists in conservation and management. Additionally, species distribution modelling serves as a numerical tool to gain insights into species distribution, widely used in natural sciences. In this context, *R. aucheri* will be modelled to investigate the impacts of climate on its distribution. *R. aucheri* is a perennial plant with tuberous roots and relatively short stems. Its leaves are palmate, divided into three lobes, with shallow to deeply incised margins. The flowers are arranged in a cyme inflorescent, with a hairy achene and a beak measuring 1.5 to 2.5 millimetres in length. The distribution areas of this plant are primarily in mountainous regions. The most important habitats are as follows: the Alborz Mountain range in the provinces of Mazandaran (Haraz), Tehran (Shamshak), and Karaj (Callous, Abali), as well as the Zagros Mountain range in the provinces of Kurdistan, Markazi (Kuh-e Sefidkhani), Zanjan (Kuh-e Belqis), Kermanshah (Kuh-Bazab), Isfahan (Kuh-e Bidak and Karkas, Golestan Kuh), Yazd (Kuh-e Barfkhane), and Fars (Kuh-e Bel). As a result, the current study was aimed at achieving the following goals for the aforementioned *R. aucheri* species in Iran: (i) Determining the most significant climatic and ecological factors that influence the distribution patterns of this species; (ii) modeling the suitable distribution areas for *R. aucheri* in Iran based on current climatic and environmental conditions; (iii) assessing potential suitable regions and analyzing trends in the distribution of *R. aucheri* under projected climate scenarios for the 2050s and 2070s; (iv) Providing critical insights to assist decision-makers in planning future conservation strategies.

MATERIALS AND METHODS

Species data collection

To demonstrate and define climatic conditions and how changes in these conditions affect plant distribution, the range and geographical scope of plant distribution are utilized. The species distribution data consist of 55 points derived from field studies and various herbariums such as TARI and ALUH (abbreviated according to Thiers 2020). The collected geographic locations of the species, along with previous records, were used as observations for modeling purposes. For this modeling, the latitude and longitude of the presence locations of *R. aucheri* were determined using Google Earth app. The study area in this research is Iran, located between 25 to 40 degrees north latitude and 44 to 64 degrees east longitude (Fig.1). The areas under study include the northern slopes of Alborz in Mazandaran Province, part of Ti-Balqis mountain in Zanjan Province, part of Zagros mountainous areas of Kurdistan Province, Hamadan, Kermanshah, Lorestan (Aligodarz), Isfahan (Chadgan, Semirom), Karkas Mountains, Golestankouh, Kohkiluyeh and Boyer Ahmad (Siskkht), Bakhtiari (Lordgan), Fars (Mount Bel, Park Bemo), Tehran (Taleqan, Karaj Valley, Kandotan, Tochal, Shemshak), southern slopes of Damavand, Markazi (Sefidkhani mountain). These areas are mountainous, except for the areas in Mazandaran Province, which have a humid climate, other areas have mostly dry and cold climates.

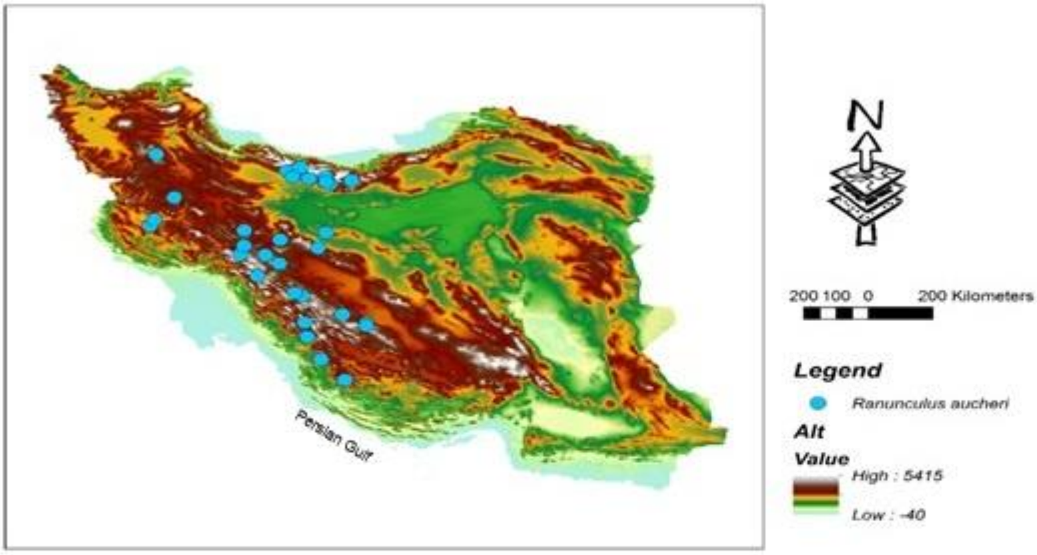

Fig. 1. Species distribution on the topographic Map of Iran.

Environmental data

Initially, to select the most important habitat and climatic variables from the various variables extracted from different sources (Table 1), the Jackknife test was employed. Based on the results and expert opinion, certain variables were selected, and then the Pearson correlation test was used to prevent collinearity among the variables. After the final determination of the variables, the climatic variables for future modeling were based on the RCP2.6 scenarios (with a CO_2 concentration of 490 ppm and a population of 7 billion by the end of 2100) as an optimistic scenario, and the RCP8.5 scenarios (with a CO_2 concentration of 1370 ppm and a population of 12 billion by the end of 2100) as a pessimistic scenario (IPCC, 2014). The General Circulation Models (GCMs) for both the 2050 and 2080 timeframes were obtained from the website www.worldclim.org. All stages of data preparation and editing were carried out in the ArcGIS 10.3 software environment.

Modeling method

For modeling species distribution, the SDM (Species Distribution Modeling) tool was used in the R software environment (R Development Core Team 2017) along with the BIOMOD2 package (Thuiller 2003; Thuiller *et al.* 2009). To process various models, the following algorithms were employed: GLM (Generalised Linear Models), ANN (Artificial Neural Network), GBM (Generalized Boosting Method), RF (Random Forest), and MARS (Multivariate Adaptive Regression Splines). To reduce uncertainty, the ensemble method was utilized to combine the algorithms. The True Skill Statistic (TSS) index was used to evaluate the accuracy of the model performance (Table 2; Fig. 2). This research was conducted based on climatic and habitat variables such as mean temperature, precipitation, soil depth, radiation, etc. (Table 1) to obtain the climatic suitability map of the species under each scenario for the two timeframes of 2050 and 2080. The results were analyzed and compared.

Table 1. Environmental variable applied to *R. aucheri* distribution model in the two climatic times.

Variables	Sources
BIO1 = Mean Annual Temperature (mm)	www.worldclim.org
BIO2 = Range of Daily Temperature (°C)	www.worldclim.org
BIO4 = Seasonal Temperature (Standard Deviation 100%)	www.worldclim.org
BIO5 = Maximum Temperature of the Hottest Month (°C)	www.worldclim.org
BIO6 = Mean Temperature of the Coldest Month (°C)	www.worldclim.org
BIO7 = Annual Temperature Range (°C)	www.worldclim.org
BIO12 = Annual Precipitation (mm)	www.worldclim.org
BIO14 = Precipitation of the Driest Month (mm)	www.worldclim.org
BIO15 = Seasonal Precipitation (Constant Coefficient; mm)	www.worldclim.org
BIO17 = Precipitation for the Three Driest Months (mm)	www.worldclim.org
BIO18 = Precipitation for the Three Warmest Dry Months (mm)	www.worldclim.org
Slope (degrees)	
Elevation (meters)	www.worldgrids.org
	www.isric.org
Depth to Bedrock (cm)	www.soilgrid.org

Table 2. Classification of model performance accuracy based on the TSS index.

Model Performance Accuracy	**TSS**
Excellent	0.80–1.00
Good	0.60–0.80
Fair	0.40–0.60
Poor	0.20–0.40
Failed	0–0.20

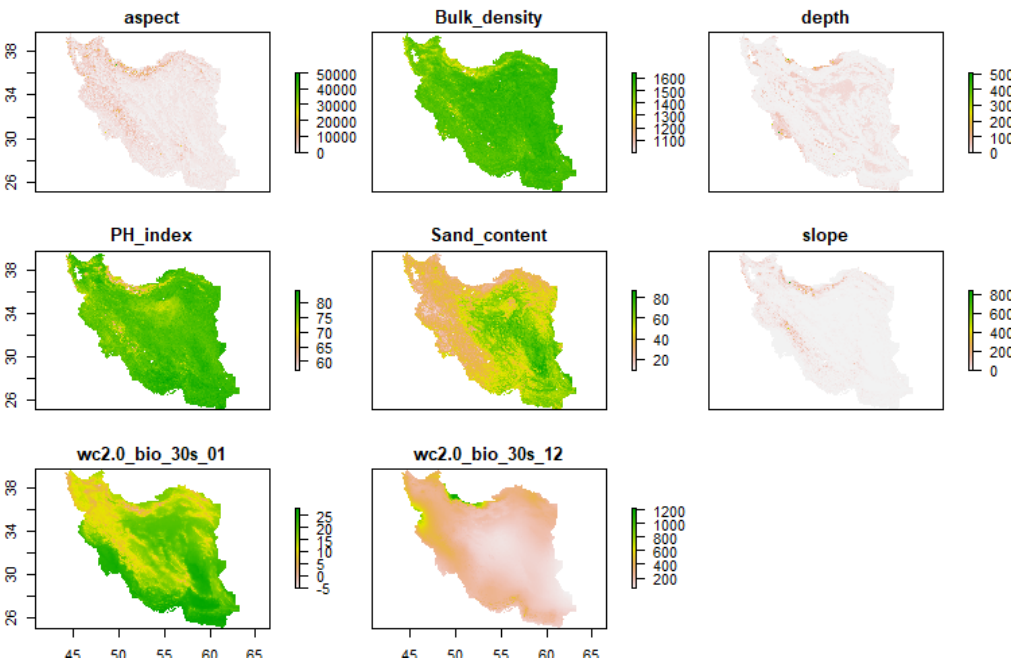

Fig. 2. Evaluation of model performance based on the TSS index.

RESULTS

The results of the correlation test indicated that 8 variables were selected as the final variables for modeling. These variables are: annual precipitation (BIO12), mean annual temperature (BIO1), slope, depth to bedrock, soil particle density, pH index, sand content, and Bulk density (Fig. 3). Based on the TSS evaluation index, the modeling of the distribution of the target species was generally performed with excellent performance (Fig. 2). In the modeling conducted for this species, all models used, except for the artificial neural network model, which performed well, showed excellent performance according to Fig. 2. The most important variables influencing the distribution of these species, according to the modeling results, were temperature, soil depth, precipitation, and sand content, in that order.

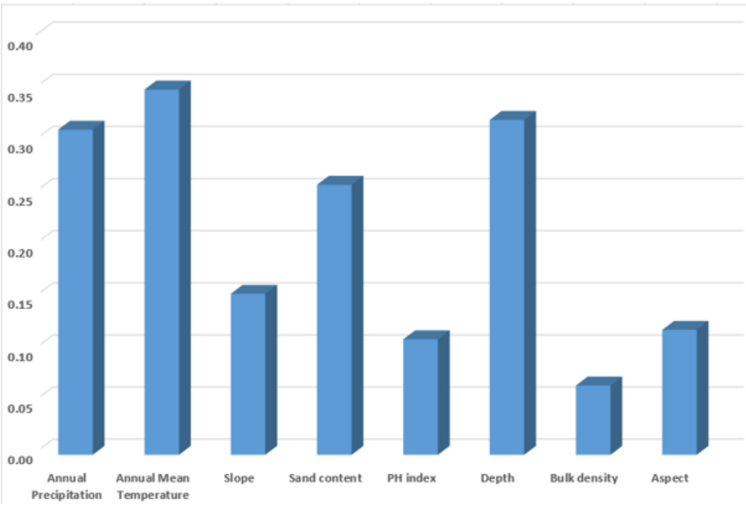

Fig. 3. Final variables selected for modeling.

According to the above map (Fig. 4) and Table 3, climate change has affected this species. In all scenarios, we have observed increases, decreases, and changes in the species range. However, the most significant reduction occurred in the pessimistic scenario for the year 2080, with a 72.47% decrease and a change of 67.12% in the species range.

Table 3. The effect of climate change under different optimistic and pessimistic scenarios by percentage.

Items	**RCP 8.5**		**RCP 2.6**	
	Period 2080	**Period 2050**	**Period 2080**	**Period 2050**
Reduction percentage	72.47	56.66	43.77	40.83
Increases percentage	5.34	14.97	10.88	12.47
Changes in the species range	67.12-	41.68-	32.86-	28.35-

The results of the modeling of the *R. aucheri* indicate the potential distribution of this species in the Central Alborz Mountains and the Kurdistan region of the Zagros mountains. Fig. 4 shows the effect of climate change under different optimistic and pessimistic scenarios in various years in a single panel. According to Fig. 5 and Table 3, climate change has impacted this species, with increases, decreases, and changes in the species range observed across all scenarios. However, the most significant reduction was related to the pessimistic scenario for 2080, with a 72.47% decrease and a 67.12% change in the species range.

DISCUSSION

In recent decades, climate change has impacted natural and human systems across all continents and oceans. The observed effects of climate change, regardless of their cause, indicate the sensitivity of natural and human systems to climate variations (https://ar5-syr.ipcc.ch).These significant changes have substantial effects on species biodiversity, affecting phenology, distribution, population, and ecosystem levels. It is noteworthy that many changes in species distribution have been reported. Climate change may lead to the expansion of some species; however, it is mostly believed that climate change has primarily contributed to the decline of species, as desert ecosystems have expanded and tree lines in mountainous systems have shifted and become restricted (Araujo & Guisan 2006).

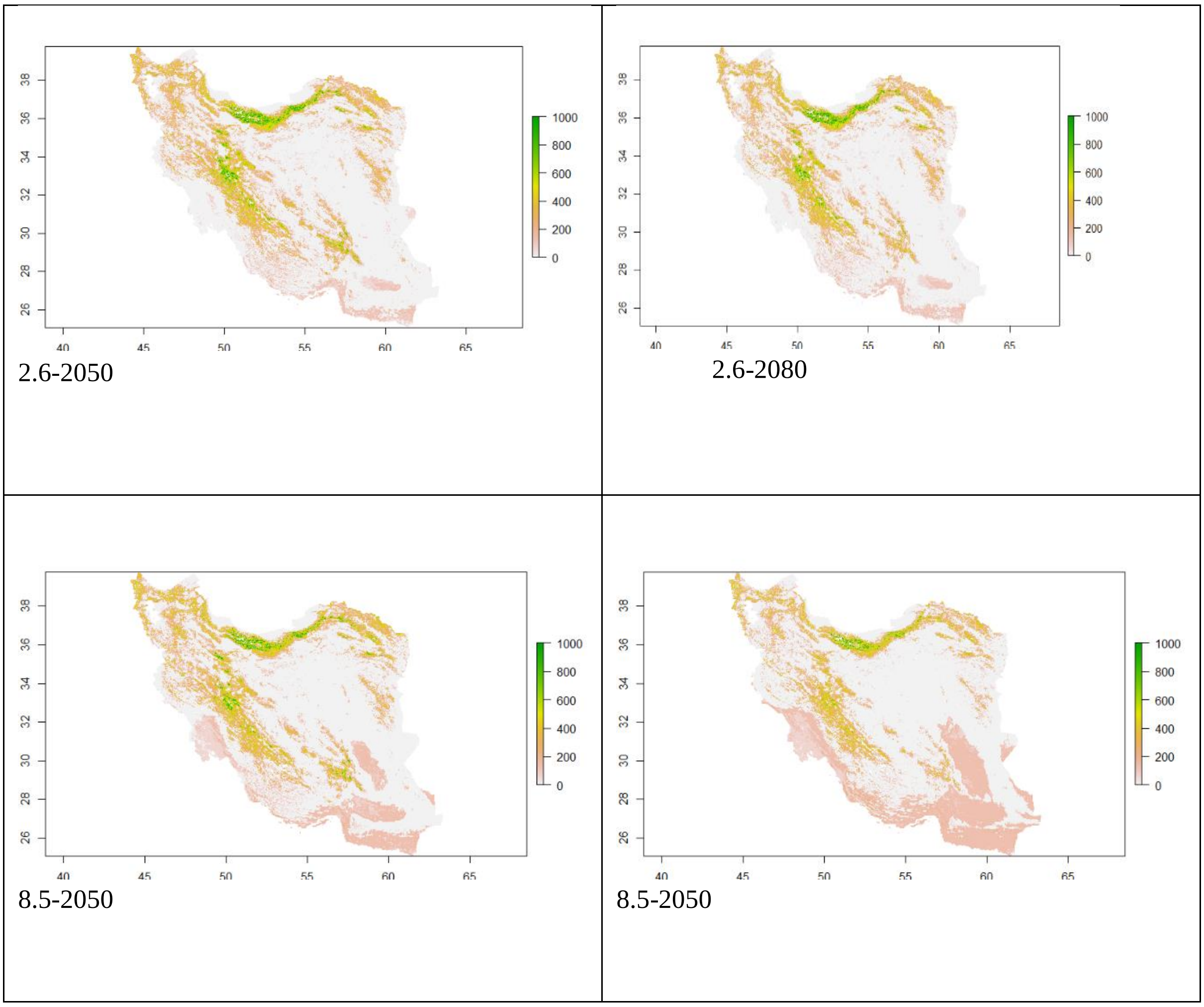

Fig. 4. The effect of climate change under different optimistic and pessimistic scenarios in various years is shown in one panel.

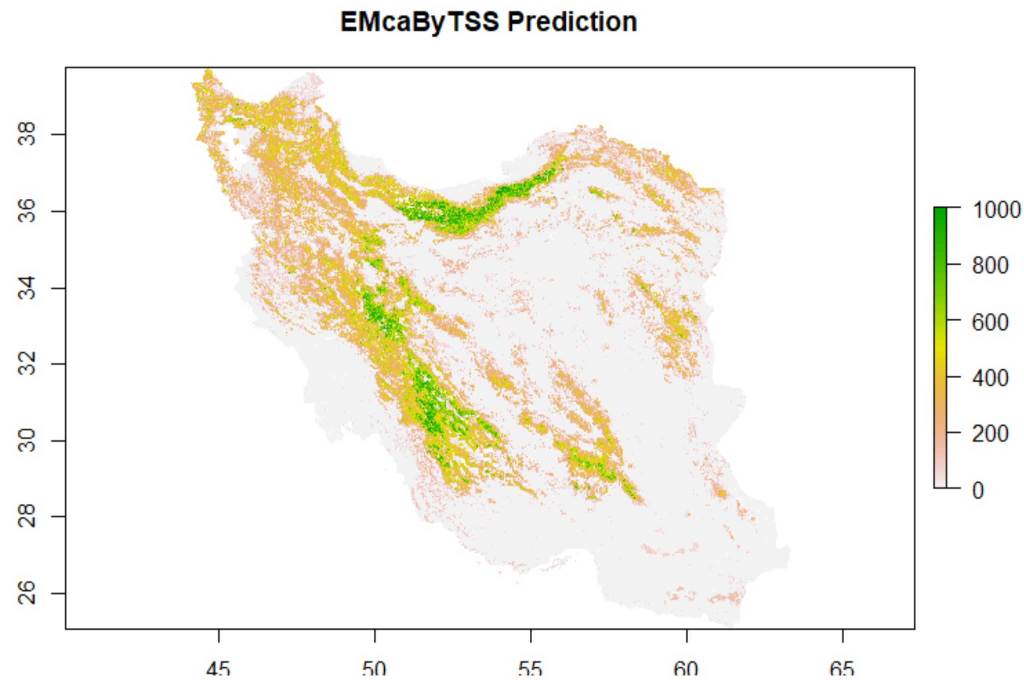

Fig. 5. Potential distribution of *R. aucheri* resulting from the consensus of the reviewed models under current conditions.

In this study, the species complex *R. aucheri* was modelled to examine the impacts of climate on species distribution, and the most important variables in determining the species distribution were evaluated. In the modeling conducted for this species, all models used, except for the artificial neural network model, which performed well, showed excellent performance. The most important variables influencing the distribution of these species, according to the modeling results, were temperature, soil depth, precipitation, and sand content, in that order (Fig. 2). The reason why seasonal temperature changes are considered more important than other variables are the significant spatial variation of temperature in the Zagros region. The results of studies by Ugurla and Oldeland (2012) in Turkey also support this idea. Additionally, Naghipour Borj *et al.* (2019) and Rana *et al.* (2017) identified temperature as the most important influencing factor among the variables they examined for the *Fritillaria* species. Hosseini *et al.* (2024) study on effects of climate change on biodiversity and species distribution on two thyme species, showed how climate change has drastically reshaped habitats, resulting in significant extinctions, particularly among sensitive species, which consequently endangers agricultural productivity and food security. The modeling results for the *R. aucheri* indicate its potential distribution in the Central Alborz Mountains and the Kurdistan region of the Zagros. The species in question exhibits different reactions to environmental changes based on its ecological characteristics and initial habitat conditions. Generally, these reactions manifest in three strategies: adaptation to changes, migration, and ultimately species extinction. If a population cannot choose the first two strategies for various reasons, the species population is doomed to extinction. The nature of climate change is such that these changes are occurring more rapidly than natural climate fluctuations, resulting in a lack of time as an ecological resource for many species, preventing them from adapting to environmental changes. Even when sufficient time is available, the adaptation process in the genotype and phenotype of the species requires enough genetic diversity within the population. On the other hand, migration as a strategy to cope with environmental changes necessitates not only the inherent capability of the species for relocation but also favourable environmental conditions, such as the presence of migration corridors and the absence of dispersal barriers. Overall, species respond to environmental changes, and these changes will vary in predictions for future time scales based on the type of scenario used for environmental description and forecasting. Franklin (2013) also, noted the utility of SDMs for "interpolation," which enhances our understanding of species distributions in areas lacking exhaustive data. It underscores the role of SDMs in biodiversity inventories and reserve design, showcasing how these models can fill geographic knowledge gaps. Researchers have cited the upward movement of plant species in recent decades as an example of species shifting due to climate change (Walther *et al.* 2002; Hörandl *et al.* 2005). Thuiller (2007) also considered one of the most important effects of climate change to be the geographic range shifts of plant species. He stated that increasing temperatures would lead to the movement of species in the Northern Hemisphere towards higher altitudes. In similar studies, Rana *et al.* (2017) and Haidarian Aghakhani and colleagues (2017) predicted the distribution of oak species (*Quercus brantii* Lindle.) in Iran, arriving at similar conclusions. They also forecasted that the oak habitat would shift to higher altitudes with greater precipitation. The effects of climate change under optimistic and pessimistic scenarios have been modelled for the species *R. aucheri* for 2050 and 2080. According to the results, this species will experience a reduction in its range due to climate change, while also being introduced to other areas, leading to an overall increase. In the optimistic scenario for 2050, we will see a 40.83% reduction and a 12.47% increase in the species, resulting in a net change of -28.35% in its range. In 2080, we will see a 43.75% reduction and a 10.88% increase, leading to a net change of -32.86% (a 4.51% greater reduction compared to 2050). In the pessimistic scenario, in 2050, we will observe a 56.66% reduction and a 14.97% increase, resulting in a net change of -41.68% in the species range (which is 13.33% greater than the optimistic scenario). In 2080, a 72.47% reduction and a 5.34% increase are reported, leading to a net change of -67.12% (34.26% greater than the optimistic scenario). Also, Babanezhad & Naqinezhad (2024) by elucidating the intricacies of SDMs and their application, offer a blueprint for advancing research and practical conservation efforts amid ongoing environmental change.

CONCLUSION

Climate conditions changes affect the plant distribution. To predict the climatic effects on the spatial distribution of the *R. aucheri*, five species distribution modeling methods, using the SDM tool was used in the R software under the scenarios of the RCP8.5 and RCP2.6 models for two-time scales: 2050 and 2080. The results showed that, the most important variables influencing the distribution of these species, according to the modeling results, were temperature, soil depth, precipitation, and sand content. The overall conclusion from these reports is that the least change in range will be -28.35% in the optimistic scenario in 2050, while the greatest change will be -67.12% in the pessimistic scenario in 2080. Therefore, the results of this research can be utilized for conservation and management programs for the *R. aucheri*. The application of SDM techniques illustrates their utility in conservation planning amidst ongoing environmental shifts. Findings from this study will inform conservation strategies and measures needed to mitigate climate impacts on biodiversity. Recommendations include cultivating *R. aucheri* in specified elevations to ensure species survival.

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