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Research Article

Climate niche modeling of *Scorpio kruglovi* (Scorpiones: Scorpionidae) in Iran

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Abstract

Species distribution models (SDMs) are one of the most effective tools that determine the factors responsible for shaping the genetic structure of different taxa. These algorithms integrate the presence points and environmental predictors to estimate the probability of species occurrence across geographical areas. In the present study, we predicted the climate niche of *Scorpio kruglovi* (Scorpiones: Scorpionidae) in Iran using eight uncorrelated bioclimatic variables and occurrence localities. This species was long considered a subspecies of *S. maurus* but later in 2015, it was recognized as a distinct species. The area under curve (AUC) value of 0.975 indicated the excellent discriminative performance of the MaxEnt algorithm. The precipitation seasonality, minimum temperature of the coldest month, and precipitation of the coldest quarter had the highest percentage of contribution (63.3%) in building the model. The response curves suggested that *S. kruglovi* prefers the parts of Iran having 64-79% precipitation seasonality, 110-130 mm precipitation of the coldest quarter, and -7 to -13 ^{0}C minimum temperature of the coldest month. The southern half of the country was predicted as unsuitable habitats for the species occurrence. Our findings confirmed two geographically distinct suitable habitat patches in the northeast and northwest of Iran. Combining the obtained climate niche map with future genetic data is an effective approach for determining the boundaries of spatial patterns of intraspecific genetic variation.

Keywords: Climate variables, Climate niche modeling, Habitat suitability, Iran, *Scorpio kruglovi*.

Introduction

Scorpions are venomous and predatory arthropods distributed all over the world except Antarctica and Greenland (Petricevich, 2010). They are valued due to their important biological, ecological, and medical attributes i.e. deadly venom (Cao et al., 2014; Asslan faal et al., 2015). So far, 18 families and 2200 species have been identified around the world (Soleglad & Fet, 2003; Prendini & Wheeler, 2005), of which 68 species exist in Iran; one of the most important hotspots for scorpions in the world (Ward et al., 2018; Kazemi et al., 2021). Interestingly, 61% of the identified species are endemic to Iran (Barahoei et al., 2020). Iran is located in the transition zone of Afrotropical, Oriental, and western Palearctic zoogeographic regions (Zehzad et al., 2002; Ghassemi-Khademi, 2014). Therefore, owing to the high ecological, biological and geographical diversity, a high degree of endemicity of scorpions exists in Iran which has led to spatial, temporal, and trophic niche partitioning among the species.

Since the climate of Iran is generally arid to semi-arid (Ghorbani, 2013) and the scorpions of the Iranian plateau are highly adapted to hot, dry, and desert conditions, it is expected that their known species richness could be a serious underestimate (Barahoei et al., 2020). Only a few studies have been conducted on the ecological requirements of scorpions in Iran (Jalali & Rahim, 2014; Hosseinzadeh, 2020). Detailed knowledge of their geographic boundaries and ecological requirements is mandatory to devise an effective conservation strategy. Therefore, increasing our knowledge about these venomous arthropods can help reduce the adverse effects of scorpion sting cases in the country.

Scorpio kruglovi Ehrenberg, 1829 (Scorpiones: Scorpionidae) is a digger scorpion that has been reported in 11 provinces of Iran (Barahoei et al., 2020). In addition to Iran, the distribution range of this species includes seven Asian countries including Iraq (Khalaf, 1962; Vachon, 1966; El-Hennawy, 1992; Fet & Lowe, 2000; Mohammad et al., 2017), Syria (Birula, 1910; El-Hennawy, 1992; Fet & Lowe, 2000; Talal et al., 2015), Kuwait, Qatar (El-Hennawy, 1992; Fet & Lowe, 2000), Jordan (El-Hennawy, 1992; Fet & Lowe, 2000; Talal et al., 2015; Amr et al., 2016), Saudi Arabia (Fet & Lowe, 2000) and Turkey (Talal et al., 2015).

Scorpio kruglovi was long considered a subspecies of *S. maurus.* Talal et al. (2015) described this scorpion as a distinct species. Although no deaths have been reported from the venom of this species, its sting is very painful and is one of the important public health concerns in Iran (Vazirianzadeh et al., 2013). Determining habitat requirements and suitable conditions for the occurrence of the species is key to prioritizing areas for species conservation and reducing the incidences of scorpion stings.

Species distribution models (SDMs) are the most effective tools for devising conservation programs of biodiversity. These algorithms integrate the occurrence points and environmental predictors to estimate the probability of occurrence of species across geographical areas (Nasrabadi et al., 2018; Ghassemi-Khademi et al., 2021a,b). They provide some valuable information about suitable conditions required for the survival and reproduction of target species or communities at desired geographic scale (Guisan & Thuiller, 2005). The growing use and popularity of SDMs are mainly due to the useful information they provide for a species

conservation program (Bulluck et al., 2006; Hosseinzadeh, 2020). Only a few studies have attempted to determine the habitat suitability of scorpions in Iran (e.g. Haghani et al., 2020; Hanafi-Bojd et al., 2020; Hosseinzadeh, 2020; Mirshamsi, 2013; Rafinejad et al., 2020; Kazemi et al., 2021); all of which confirm the efficiency of SDMs in diverse perspectives.
In the present study, we used SDMs to 1) predict the climate niche and spatial pattern of climatically suitable habitats of *S. kruglovi* across Iran and 2) determine how climatic variables affect its geographic range.

Materials and methods

A total of 21 georeferenced occurrence localities of *S. kruglovi* were compiled from the literature review (Habibi, 1971; Karataş et al., 2012; Navidpour et al., 2019; Barahoei et al., 2020; Table 1; Fig. 1). The reliability of the compiled occurrence localities was assessed by Google Earth version 7.1. The obtained number of presence points was low but well distributed across the area. The current climate variables at 30 arc-second spatial resolution were downloaded from the Worldclim database (http://worldclim.org/version2; Fick and Hijmans, 2017). These bioclimatic variables represent annual trends, seasonality, and limiting environmental factors to different organisms (Fick and Hijmans, 2017; Moreno-Amat et al., 2015). After excluding the highly correlated variables ($r \geq 0.75$; Table 2), a total of eight predictors were retained to simulate the current climate niche of *S. kruglovi* including isothermality (BIO3), temperature seasonality (BIO4), minimum temperature of the coldest month (BIO6), temperature annual range (BIO7), mean temperature of the wettest quarter (BIO8), mean temperature of the driest quarter (BIO9), precipitation seasonality (BIO15), and precipitation of coldest quarter (BIO19; Table 3).
We used the MaxEnt model to predict climatically suitable habitats of the species (Phillips et al., 2006). It has been shown that presence only (PO) modeling methods, such as MaxEnt, and ecological niche factor analysis (ENFA; Hirzel et al. 2002) have equal or better performance than presence-absence (PA) algorithms (Gibson et al. 2007; West et al. 2016; Marx and Quillfeldt, 2018). The Maxent model was run using 10 replicates, 5000 iterations, 10000 background points, a regularization multiplier of 1, and a convergence threshold of 0.00001. A complementary log-log (cloglog) was used as an output format (ranging from 0-1) to estimate the habitat suitability as it is more appropriate than the logistic format to estimate the occurrence probability and Maxent ver. 3.4.1 uses it by default (Phillips et al. 2017).
The predictive performance of the model was evaluated by the area under the curve (AUC) of the receiver operating characteristic (ROC) curve (Phillips et al. 2006). The AUC value varies between 0 to 1 and the value ≤ 0.5 means that model performance is not better than random and no discrimination exists. Moreover, an AUC value of > 0.7 indicates potentially significant discrimination while 1 indicates perfect discrimination and predictive ability (DeLeo, 1993; Swets, 1988; Phillips et al., 2006; Elith et al., 2006). Moreover, we converted the predicted climate niche map to a binary layer using the 10^{th} percentile training presence threshold to calculate the extent of suitable habitats of the species (Liu et al., 2005; Kafash et al., 2018; Ghassemi-Khademi et al., 2021).

Table 1. List of occurrence points used to predict climate niche of *Scorpio kruglovi* in Iran.

Species	Longitude	Latitude	Reference
S. kruglovi	50.6533	36.0596	Navidpour et al., 2019
S. kruglovi	50.6534	36.0651	Navidpour et al., 2019
S. kruglovi	50.7848	35.9571	Navidpour et al., 2019
S. kruglovi	50.395	35.7807	Navidpour et al., 2019
S. kruglovi	50.5972	35.816	Navidpour et al., 2019
S. kruglovi	50.6677	35.7267	Navidpour et al., 2019
S. kruglovi	48.65	34.7833	Karataş et al., 2012
S. kruglovi	47.15	34.3	Karataş et al., 2012
S. kruglovi	47.0333	35.3166	Habibi, 1971
S. kruglovi	49.3068	34.022	Navidpour et al., 2019
S. kruglovi	50.1621	33.7834	Navidpour et al., 2019
S. kruglovi	49.6675	34.433	Navidpour et al., 2019
S. kruglovi	49.6188	33.9497	Navidpour et al., 2019
S. kruglovi	49.6158	33.9827	Navidpour et al., 2019
S. kruglovi	53.1	36.5666	Karataş et al., 2012
S. kruglovi	57.3	37.4333	Karataş et al., 2012
S. kruglovi	49.65	36.05	Karataş et al., 2012
S. kruglovi	50.5666	36.4333	Karataş et al., 2012
S. kruglovi	59.5833	36.2166	Habibi, 1971
S. kruglovi	53.4333	35.5666	Karataş et al., 2012
S. kruglovi	51.4216	35.288	Navidpour et al., 2019

Table 2: Correlation matrix among bioclimatic variables. Variables showing $|r| \geq \pm 0.75$ were eliminated from the analyses.

	Bio1	**Bio2**	**Bio3**	**Bio4**	**Bio5**	**Bio6**	**Bio7**	**Bio8**	**Bio9**	**Bio10**	**Bio11**	**Bio12**	**Bio13**	**Bio14**	**Bio15**	**Bio16**	**Bio17**	**Bio18**	**Bio19**
Bio1	1																		
Bio2	-.042	1																	
Bio3	.017	.903	1																
Bio4	-.193	.162	-.265	1															
Bio5	.899	.330	.264	.072	1														
Bio6	.784	-.540	-.303	-.552	.465	1													
Bio7	-.125	.847	.538	.653	.301	-.704	1												
Bio8	.556	-.209	.021	-.532	.345	.675	-.450	1											
Bio9	.906	.119	.017	.195	.954	.527	.196	.303	1										
Bio10	.958	.017	-.043	.085	.944	.640	.068	.409	.978	1									
Bio11	.943	-.107	.089	-.495	.769	.888	-.340	.660	.741	.821	1								
Bio12	.240	-.128	.160	-.708	.058	.491	-.483	.504	-.048	.056	.461	1							
Bio13	.128	.074	.357	-.686	.035	.328	-.325	.378	-.119	-.039	.365	.956	1						
Bio14	.390	-.682	-.400	-.657	-.006	.796	-.863	.690	.045	.196	.556	.672	.464	1					
Bio15	-.399	.739	.656	.152	-.080	-.659	.646	-.479	-.273	-.337	-.397	-.208	.044	-.765	1				
Bio16	.199	.011	.300	-.718	.074	.409	-.382	.449	-.076	.020	.432	.977	.987	.547	-.017	1			
Bio17	.406	-.691	-.409	-.659	.009	.815	-.870	.684	.064	.211	.571	.647	.436	.996	-.774	.523	1		
Bio18	.332	-.706	-.425	-.664	-.067	.768	-.881	.670	-.024	.135	.506	.664	.455	.989	-.719	.546	.989	1	
Bio19	.233	.147	.379	-.602	.173	.330	-.217	.341	.019	.086	.422	.945	.967	.418	.058	.970	.393	.411	1

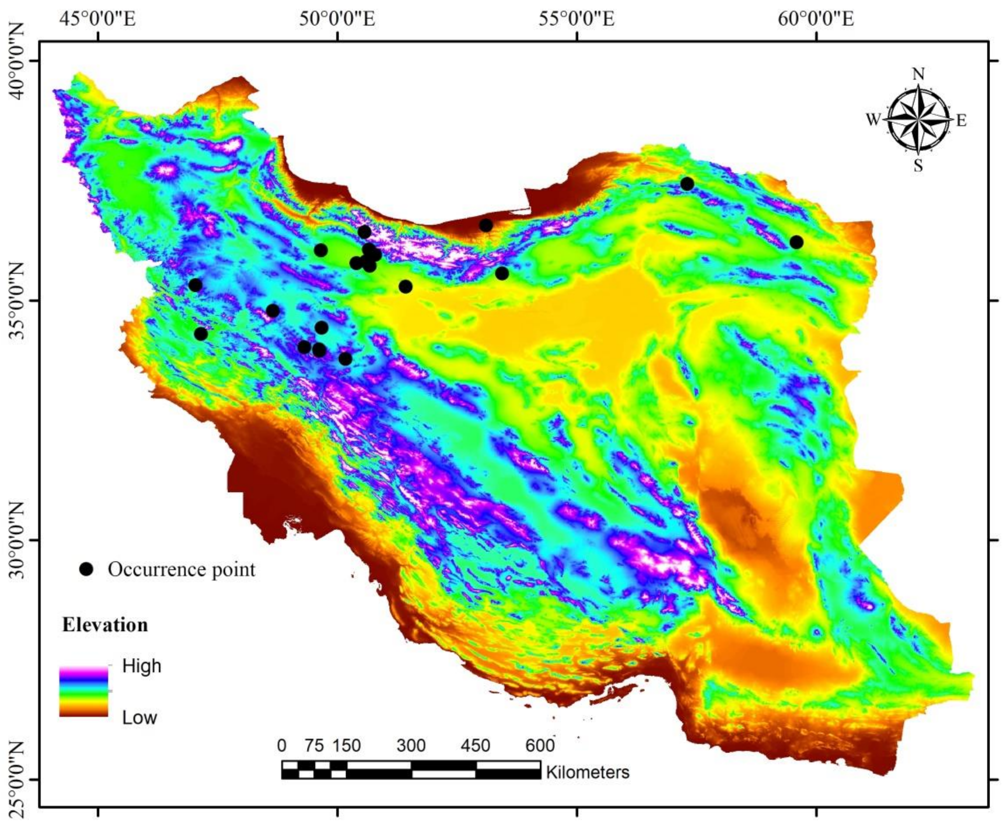

Figure 1. The geographical distribution of presence points of *S. kruglovi is* used to predict climate niches.

Table 3. Bioclimatic variables and their relative importance (in percentages) in predicting the climate niche of *S. kruglovi*. Pairwise correlation among these layers was less than 0.75.

Abbreviation	Variable	Units	Percent contribution
BIO3	Isothermality	Percent	0.9
BIO4	Temperature Seasonality	Degrees Celsius	4.8
BIO6	Minimum Temperature of Coldest Month	Degrees Celsius	20.1
BIO7	Temperature Annual Range	Degrees Celsius	9.2
BIO8	Mean Temperature of Wettest Quarter	Degrees Celsius	15.5
BIO9	Mean Temperature of Driest Quarter	Degrees Celsius	6.3
BIO15	Precipitation Seasonality	Percent	24.2
BIO19	Precipitation of Coldest Quarter	Millimeters	19

Results

The predicted map of the climate niche of *S. kruglovi* showed high discrimination performance of the MexEnt model (Fig. 2) according to training AUC±standard deviation (SD; 0.975±0.010) and testing data (0.938±0.075; Fig. 3). Precipitation seasonality, minimum temperature of the coldest month, and precipitation of the coldest quarter had the highest percentage of contribution (24.2%, 20.1%, and 19% respectively) in predicting the climate niche of *S. kruglovi* followed by mean temperature of wettest quarter, temperature annual range, mean temperature of driest quarter, temperature seasonality, and isothermality with 15.5%, 9.2%, 6.3%, 4.8%, and 0.9% contributions, respectively (Table 3). Based on the Jackknife test, the minimum temperature of the coldest month contained the most useful information and highest gain (~ 0.6) while the precipitation seasonality contained the largest volume of data than other variables for predicting the climate niche of the species (Fig. 4).

The climate niche suitability of the species showed a non-linear relationship with precipitation seasonality. The probability of occurrence of *S. kruglovi* increased to its maximum (64-79%) and then dropped sharply at levels above 80%. Moreover, the habitat suitability of *S. kruglovi* was predicted to increase with the rise in the minimum temperature of the coldest month and then leveled off sharply at temperatures more than -7 ^{0}C. The response curve of precipitation of the coldest quarter showed a peak between 110-130 mm and habitat suitability sharply decreased in areas where the variable was less than 110 mm. Also, the habitat suitability for *S. kruglovi* decreased steeply and reached its minimum in areas with a mean temperature of the wettest quarter above 7 ^{0}C (Fig. 5). Moreover, this species prefers some parts of Iran with a temperature annual range of more than 40 ^{0}C, mean temperature of the driest quarter between 23-27 ^{0}C, temperature seasonality above 9.5 ^{0}C, and isothermality less than 37%. Based on the potential distribution map of *S. kruglovi* (Fig. 2), the southern half of Iran has predicted an unsuitable habitat for the species occurrence. However, high habitat suitability was detected in a significant area of northeast, northwest, and some parts of north and west Iran. Our results also revealed that 7.95% of the study area is suitable for *S. kruglovi*.

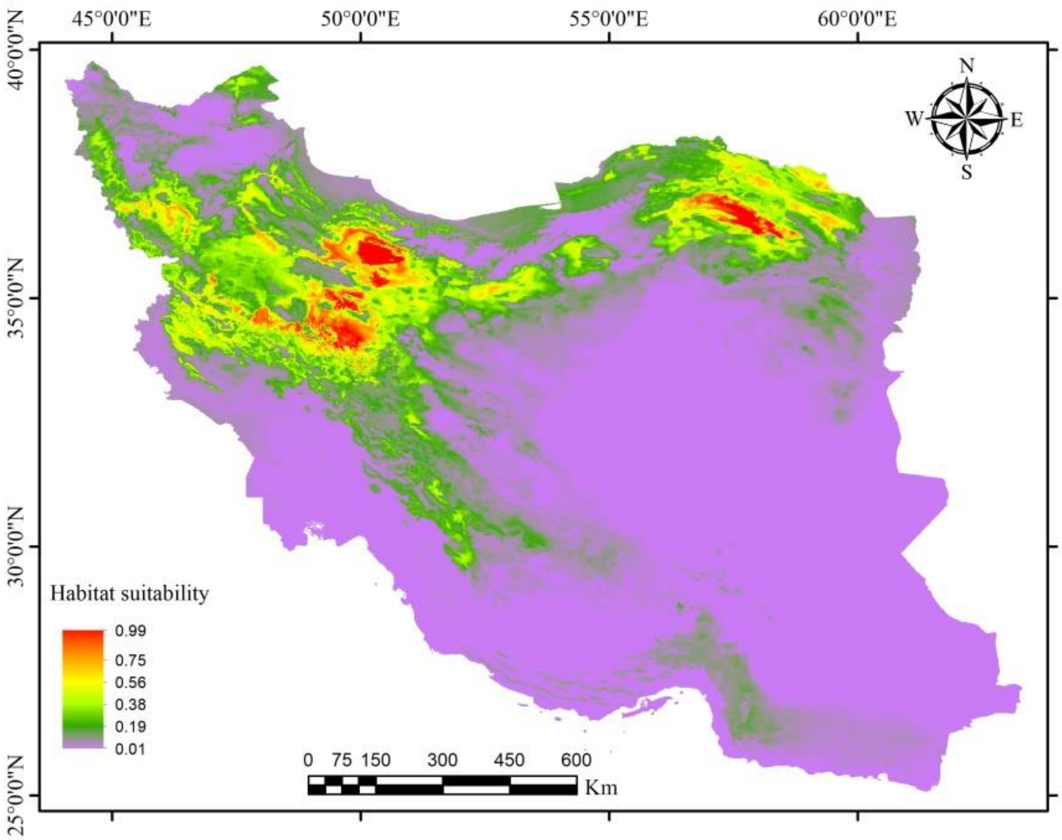

Figure 2. Predicted climate niche of *S. kruglovi* in Iran based on the Maxent model.

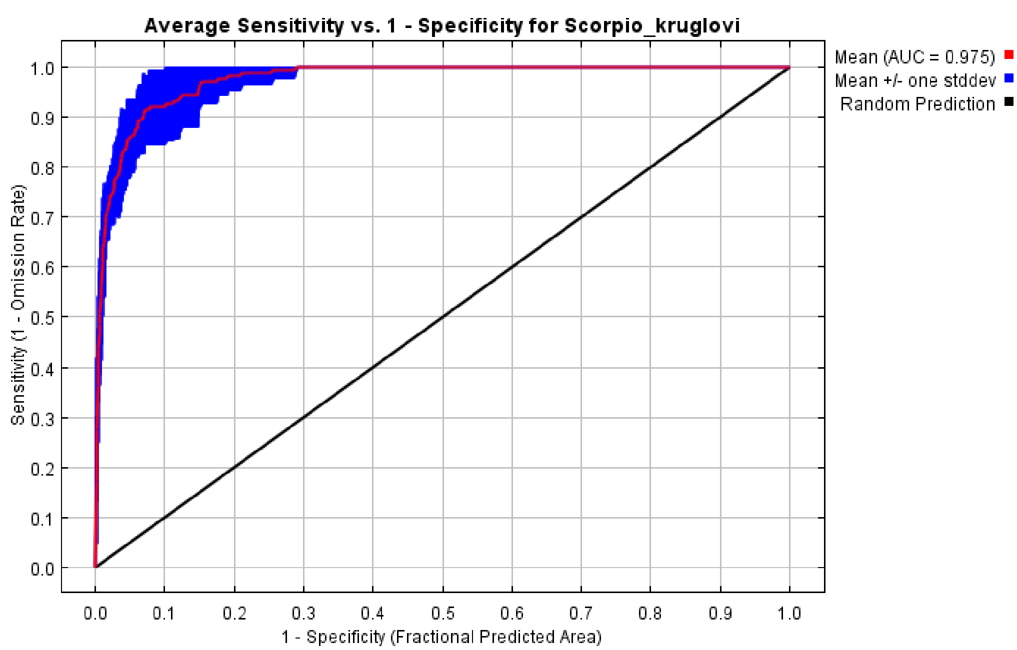

Figure 3. The graph of the receiver operating characteristic (ROC) curve for the climate niche of *S. kruglovi* in Iran.

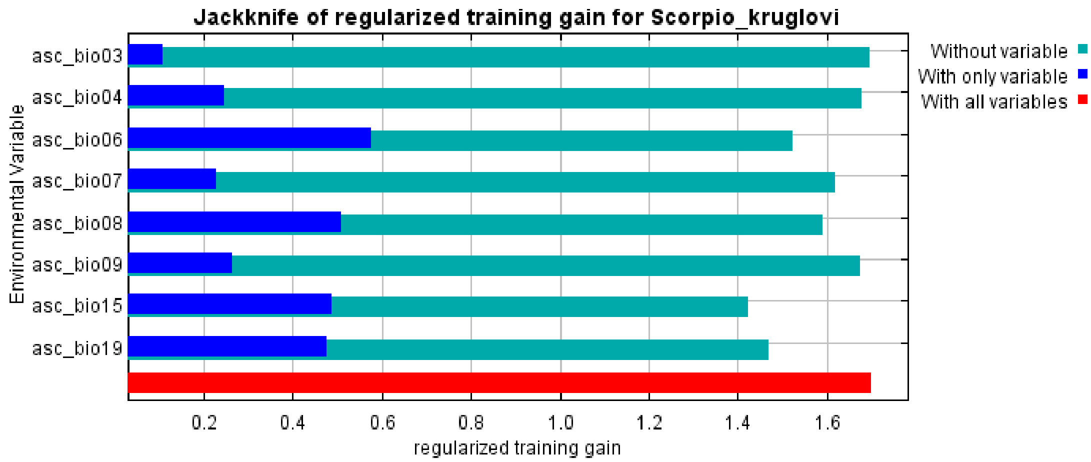

Figure 4. The relative importance of climate variables used for predicting the climate niche of *S. kruglovi*.

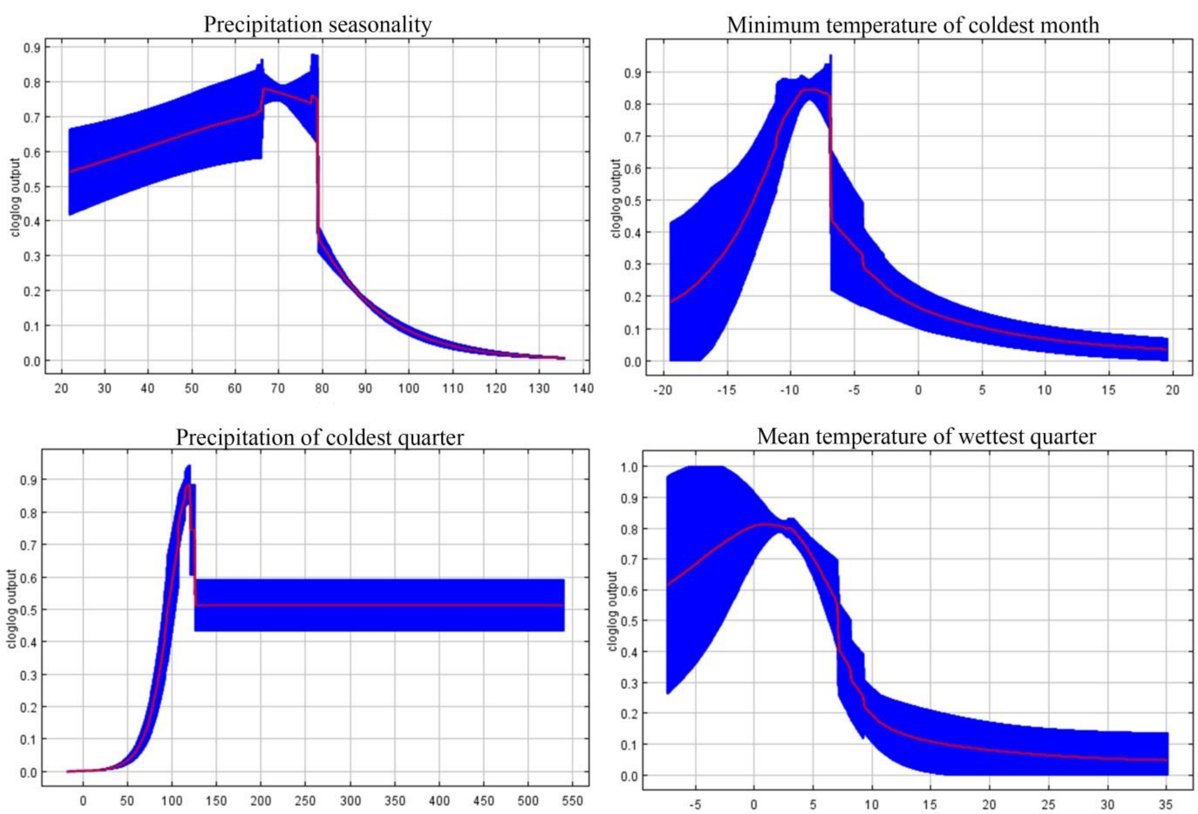

Figure 5. Response curves of the most influential climate variables in predicting climate niche of *S. kruglovi*.

Discussion

Iran is one of the most important hotspots for scorpions in the world (Ward et al., 2018; Kazemi et al., 2021) therefore, the ecological requirements of Iranian scorpions need to be investigated. Besides the biological and evolutionary value of scorpions as one of the oldest animal groups on our planet (Dunlop & Selden, 2013; Ureta et al., 2020), the therapeutic properties of their venom have also been proven in the treatment of some human diseases including cancer and bacterial infections (Ortiz et al., 2015). Hence, there is a need to undertake ecological and biological studies on Iranian scorpions with a viewpoint on their conservation and socioeconomic uses. In the present research, we evaluated the effects of climatic conditions on the potential distribution of an Iranian digger scorpion, *S. kruglovi*. Our results indicated that the potential range of *S. kruglovi* is limited to northeast, northwest, and some parts of north and west of Iran. The results revealed that precipitation seasonality and minimum temperature of the coldest month were the two important limiting factors responsible for shaping its climate niche. Our findings are inconsistent with Haghani et al. (2020) who indicated that the minimum temperature of the coldest month is one of the effective variables on the distribution pattern of three species of digger scorpions in Iran i.e., *Odontobuthus doriae*, *O. bidentatus*, and *S. maurus*.

The potential distribution of *S. kruglovi* was strongly restricted in two relatively isolated habitat patches located at the marginal parts of the species distribution range in the northeast and northwest of Iran. Although no data is available about the phylogeny of *S. kruglovi* in Iran, two distinct phylogenetic lineages probably exist in two relatively isolated ecological niches. The mentioned areas are predicted to have high suitability for *S. kruglovi* in Iran and provide the necessary ecological requirements for the survival and reproduction of this species. Combining future genetic data with the obtained ecological niche predictions is an effective approach for determining the spatial patterns of intraspecific genetic variation and providing greater insight into the species boundaries.

The distribution of different species of scorpions is highly related to climatic factors, especially precipitation and temperature (El Hidan et al., 2017). Koch (1981) indicated that the scorpion biodiversity is highly dependent on three factors including temperature, precipitation, and species competition. Consistent with these findings, in the present study, hydrological (precipitation seasonality), and thermal-related (minimum temperature of the coldest month) variables showed significant effects on predicting the species' climate niche of the species.

Although the species richness of scorpions is much higher in the southern half of Iran than in the northern half (Rafinejad et al., 2020), this species has not been reported in the southern half of Iran so far. Also, our potential distribution map did not show suitable climate conditions for this species in southern Iran. The habitat suitability declined significantly in the areas where the precipitation seasonality and minimum temperature of the coldest month reached more than 80% and -7 ^{0}C, respectively. Consequently, following Liebig's law of the minimum, these two factors are likely to be the limiting ones and do not warrant the expansion of *S. kruglovi* to the southern regions of Iran.

Based on our selected binary threshold (i.e. 10th percentile training presence) about 7.95% of the country (~ > 131000 Km^2) is climatically suitable for the species' occurrence. However, the area with potential suitability for *S. kruglovi* is probably less than that hypothesized. Because in the northern half of Iran (especially in provinces such as Tehran, Alborz, Qazvin, Khorasan, etc.) human activities such as urban development, industrial, and agricultural activities have severely destroyed natural habitats. These activities are threatening factors to the survival and reproduction of many animal species, especially different species of scorpions since they are sensitive and vulnerable to changes in their natural habitats (Ureta et al., 2020).

In this survey, we built our model based on 21 occurrence points only, but this species will probably be recorded in more areas of Iran in the future field surveys and will complement our knowledge about its habitat characteristics, and ecological requirements. For the time being, we do not know much about the phylogeny of *S. kruglovi* and other lineages of the genus *Scorpio* in Iran. Therefore, conducting such climate niche modeling studies is the first step to determining the taxonomic status and distribution range of this species. Our results will serve as a key starting point to build appropriate strategies to device conservation programs for scorpions and establish health-related research in the field of medicines against their sting in Iran.

Conclusion

Our results revealed the efficiency of the MaxEnt algorithm to build the climate niche of *Scorpio kruglovi*, one of the species of digger scorpions in Iran. The precipitation seasonality and minimum temperature of the coldest month are the two most important climatic factors affecting its life cycle in Iran. The southern half of the country is found unsuitable for the species occurrence. Due to the strong correlation of the distribution range of this scorpion species with climatic factors, we suggest that future studies should focus on the effects of climate change on possible range shifts from its potential distribution. Owing to the high level of the model prediction (AUC = 0.975), our results can be used in designing and executing conservation programs with a high degree of reliability.

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