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Effect of climate change on spatial distribution of scorpions of significant public health importance in Iran

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ABSTRACT

Objective: To establish a spatial geo-database for scorpions in Iran, and to identify the suitable ecological niches for the most dangerous scorpion species under different climate change scenarios.

Methods: The spatial distribution of six poisonous scorpion species of Iran were modeled: *Hemiscorpius lepturus*, *Androctonus crassicauda*, *Mesobuthus eupeus*, *Hottentotta saulcyi*, *Hottentotta zagrosensis*, and *Odontobuthus (O.) doriae*, under RCP2.6 and RCP8.5 climate change scenarios. The MaxEnt ecological niche model was used to predict climate suitability for these scorpion species in the 2030s and 2050s, and the data were compared with environmental suitability under the current bioclimatic data.

Results: A total of 73 species and subspecies of scorpions belonging to 19 genera in Iran were recorded. Khuzestan Province has the highest species diversity with 34 species and subspecies. The most poisonous scorpion species of Iran are scattered in the semi-arid climates, at an altitudinal range between 11 m and 2 954 m above sea level. It is projected that *O. doriae*, *Androctonus crassicauda* and *Mesobuthus eupeus* species would be widely distributed in most parts of the country, whereas the most suitable ecological niches for the other species would be limited to the west and/or southwestern part of Iran.

Conclusions: Although the environmental suitability for all the species would change under the two climate change scenarios, the change would be more significant for *O. doriae* under RCP8.5 in the 2050s. These findings can be used as basis for future studies in the areas with the highest environmental suitability for the most dangerous scorpion species to fill the gaps in the ecology of scorpion species in these areas.

KEYWORDS: Scorpion; Niche modeling; Climate change; Iran

1. Introduction

Considered as a living fossil, scorpions are one of the oldest arthropods. They are poisonous with hunting behavior, and they pose a varying degree of threat to human health. Scorpions are able to adapt to life in different habitats, such as grasslands, savannas, deciduous forests, montane pine forests, rain forests and caves, and are also active at a wide range of altitudes[1]. Most scorpion species prefer arid areas and unlike most organisms, species richness and diversity of scorpions are higher in these areas[2]. This is due to their ability to adapt to higher temperatures and conserve water for long a period of time. The nocturnal activity of scorpions and burrowing behavior which allow them to seek shelter from higher temperatures also favor their adaptation to life in habitats with higher temperatures. Earlier research studies identified temperature and rainfall as the most effective environmental variables affecting the distribution of scorpions. On the other hand, vegetation was found to be the least important environmental variable[3].

Temperature, light, and humidity are the most important environmental factors that affect the activity of scorpions. Another

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study confirmed that climate factors and habitat type are the most important determinants of the distribution of these venomous arthropods. There is also a strong association between land surface temperature and population density of scorpions[4]. Some experts, however, believe that soil texture, type, and depth are the most important environmental factors which affect the population of some scorpion species[5]. In most cases, there are two peaks in the activity of scorpions during a nycthemeron; nightfall and early morning[4]. A recent review of the status of scorpion sting cases in relation to climatic variables using time series model indicated that temperature plays an important role in scorpion sting[6]. A similar study in Algeria also confirmed a relationship between temperature and scorpion sting[7].

In general, scorpions are among the arthropods which prefer desert habitats, and they do not normally enter into human settlements. But today, with the increasing human population and changing land use, particularly in the urban areas, these organisms are often found nesting near human settlements. Scorpion sting is a serious health problem in underdeveloped tropical and subtropical countries. Envenomation due to scorpion sting often causes mild symptoms such as localized skin rashes but can lead to widespread neurological, cardiovascular, and respiratory complications, and can sometimes be fatal. This is a major public health concern particularly in areas with high prevalence of poisonous scorpions. The first step in understanding the dispersal of various species of poisonous arthropods in an area is the collection of quality data on their taxonomy and geographical distribution. Recent studies on the mapping of scorpion species have attempted to determine their geographical distribution in relation to the environmental variables at the collection sites using ecological niche models[8,9].

Scorpion sting is one of the most important arthropod associated human injuries in Iran, especially in the south and southwestern areas, with an estimated annual incidence of 54.8 to 66.0 per 100 000 populations and a mortality rate of 0.05%[10]. About 1 500 species of scorpion have been identified worldwide, 30 species of which are considered venomous and highly poisonous[11,12]. Among the Iranian scorpion fauna, 6 species are considered highly poisonous, including *Androctonus (A.) crassicauda*, *Hemiscorpius (H.) lepturus*, *Hottentotta (H.) saulcyi*, *H. zagrosensis*, *Mesobuthus (M.) eupeus*, and *Odontobuthus (O.) doriae*. An antivenom has been produced which provides a varying degree of protection against the 6 species above. Earlier studies in Iran have reported these species[13–15].

A. crassicauda is widespread and can be found in most of the provinces of Iran. It is one of the most venomous and medically important arachnids. It is the second most poisonous scorpion in Iran. Vazirianzadeh et al. reported that *A. crassicauda* was responsible for 27% of scorpion stings recorded in Ahvaz, Southwest of Iran, from April to September in 2007[16]. This rate was 29% in Khuzestan Province of Iran[17]. *A. crassicauda* specimens were commonly found

in sandy and calcareous soil areas. The most preferred habitat for this species in Iran is thorn bush steppe[18].

H. lepturus is of high medical importance, especially in children, because of its relatively painless sting. The venom of this scorpion is cytotoxic and can induce severe inflammation and injuries on the skin, and even death in some cases. It is a non-digger species and prefers warm and relatively wet areas[8].

H. saulcyi specimens have been collected from calcareous soil and at altitudes ranging between 684 and 2 025 m above sea level[19]. It is a semi-digger, classified among the poisonous scorpion species of Iran[8]. In Iran, specimens of *H. saulcyi* were collected from steppe habitats, including calcareous soils in the western areas of the country[18].

H. zagrosensis is an endemic species in Iran and found mostly in the Zagros chain region in Fars, Khuzestan, Kohgiluyeh va Boyer-Ahmad, Lorestan, and West Azerbaijan provinces. It is also found in Alamout area in Qazvin Province, located in the foothills of the Alborz Mountain[20,21]. This species, like other species of the genus *Hottentotta*, is a non-digging scorpion and prefers mountainous and rocky area habitats. It has recently been identified in the eastern region of Iraq[22].

M. eupeus is also a non-digger species, and one of the most medically important scorpions of Iran. In general, a sting from *M. eupeus* results in minor local symptoms not requiring any specific intervention[23]. The sampling sites of this species in Zanjan Province in the west of Iran included hard calcareous soil and steppe vegetation[18]. It is commonly found in populated areas and is the most widespread species in human dwellings in Iran[8].

O. doriae is a burrowing scorpion, which can dig tunnels longer than 40 cm in length. It is one of the medically important scorpions which exists in relatively high numbers in Iran[24]. Sting of this species is considered as potentially fatal, and it is responsible for most deaths due to scorpion envenomation in the central parts of Iran[23]. *O. doriae* specimens have been collected from calcareous soils and stony areas. It is mostly found in steppe habitats[18].

Climate change is an important issue in the potential spatial distribution of arthropods in future because their activities are highly dependent on environmental conditions. It is therefore recommended that all countries investigate and predict the potential effects of climate change on the important vectors/arthropods that affect community health. This would help identify susceptible areas, and to implement appropriate strategies for the prevention or reduction of vector-borne diseases/injuries. Studies on the effects of climate change on the spatial distribution of some of the most important vector-borne diseases have been conducted in some countries[25–28].

The aim of this study was to establish a spatial geo-database on the scorpion species of Iran and to find the most suitable ecological niches for the most poisonous scorpion species under different climate change scenarios.

2. Materials and methods

2.1. Data collection

All published data on the fauna, distribution, ecology, and biology of scorpions of Iran were searched for the time range of 1990–2019 from scientific databases, including Google Scholar, PubMed, Magiran, and Scopus, and the results were recorded in an Excel database. The key words were included: *Androctonus crassicauda*, *Hemiscorpius lepturus*, *Mesobuthus eupeus*, *Hottentotta sauleyi*, *Hottentotta zagrosensis*, *Odontobuthus doriae*, distribution, and Iran. Subsequently, published data on the spatial distribution of the six poisonous scorpion species were used for the modeling. In ArcGIS software, layers of the spatial distribution of the different scorpion species were matched with climatic and geographical layers. “Extract values to points” tool in ArcMap analyst was then used to extract climatic and topographic characteristics of the distribution zones of the different species. Then using the statistics tool in attribute table of scorpion’s distribution layers we calculated min, max and average for altitude, as a quantitative variable. For climate layer, which included the qualitative data (codes for different climates), we just described the percentage of collection sites for each scorpion species in different climates.

2.2. Climate change scenarios and data

The results of the research conducted by the National Climate Research Institute[29] were the basis for selecting the general circulation model in this study. The Beijing Climate Center Climate System Model version 1.1 (BCC_CSM1.1) was used in our analysis at a spatial resolution of 30 seconds (1 km²)[30]. In the present study, two scenarios were used for modeling: representative concentration pathway (RCP) 2.6 and RCP8.5. In the RCP2.6 emission scenario, CO₂ concentration is estimated to be 490 PPM by 2100, with a radiative forcing level of 2.6 W/m²[31–33]. Global change assessment modeling team at the Joint Global Change Research Institute (a branch of the Pacific Northwest National Laboratory) in the United States developed the RCP2.6 scenario[34]. The RCP2.6 scenario is considered as a stabilization scenario, without an overshoot, in which the total radiative forcing is stabilized shortly after 2100[35]. RCP8.5 scenario corresponds to the highest greenhouse gas emission trajectory among the RCPs based on the literature of the scenarios[32], and hence, also to the upper bound of the RCPs. The greenhouse gas concentrations and emission trajectories in the RCP8.5 are estimated to increase considerably over time, leading to a radiative forcing level of 8.5 W/m² at the end of the century with a temperature range between 3.5 and 4.5 °C[36]. The bioclimatic data for both scenarios for 2030s and 2050s were downloaded from www.ccafs.cgiar.org (<http://ccafs-climate.org/data>) and www.worldclim.org (http://www.worldclim.org/cmip5_30s), respectively, at a spatial resolution of 30 s. ArcMap was then used to clip the downloaded

layers to the border of Iran.

To compare the current situation of the environmental suitability for scorpions, current bioclimatic variables at the same spatial resolution (1 km²) were downloaded from the worldClim website (www.worldclim.org) and prepared in ArcMap. A total of 19 bioclimatic variables were used for the modeling (Table 1).

Table 1. Bioclimatic variables used in MaxEnt model.

Variables	Description
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 (SD × 100)
Bio5	Maximum temperature of warmest month (°C)
Bio6	Minimum temperature of coldest month (°C)
Bio7	Temperature annual range (Bio5–Bio6) (°C)
Bio8	Mean temperature of wettest quarter (°C)
Bio9	Mean temperature of driest quarter (°C)
Bio10	Mean temperature of warmest quarter (°C)
Bio11	Mean temperature of coldest quarter (°C)
Bio12	Annual precipitation (mm)
Bio13	Precipitation of wettest month (mm)
Bio14	Precipitation of driest month (mm)
Bio15	Precipitation seasonality (coefficient of variation)
Bio16	Precipitation of wettest quarter (mm)
Bio17	Precipitation of driest quarter (mm)
Bio18	Precipitation of warmest quarter (mm)
Bio19	Precipitation of coldest quarter (mm)

2.3. Modeling

The ecological niche model MaxEnt ver 3.4.1 was used to predict the environmental suitability of the six scorpion species. This model involves the use of species presence records and bioclimatic/environmental variables (as predictors) of the study area[37]. All downloaded bioclimatic data were converted to the Ascii format in ArcMap for running in the MaxEnt software. Also, the geographical coordinates of the presence of the medically important species were converted into CSV format in the Excel environment after being extracted from the sources and were examined and stored in a database. Finally, the model displayed the environmental suitability for the presence of each species as an output. Jackknife analysis of the MaxEnt model output was used to determine which climatic and environmental variables had the greatest effect on the distribution of the scorpion species.

3. Results

3.1. List of scorpion species in different parts of Iran

Firstly, a database was created for the scorpion species due to the large number of documents published on these arthropods. Accordingly, 63 papers published in the context of the Iranian scorpion fauna were entered into the database of the poisonous

arthropods of Iran (Figure 1). The results show there are 73 species and subspecies of scorpions belonging to 19 genera in three families: Buthidae, Scorpionidae, and Hemiscorpidae in Iran. Khuzestan Province in the southwestern part of Iran has the highest species diversity with 34 species and subspecies.

Table 2 shows the list of scorpion species reported from different parts of Iran. Southern provinces of the country have higher species richness than central and then northern areas.

3.2. Distribution of scorpions in different climates and altitudes

According to the Koppen climate classification, Iran has seven climates, including slightly semi-arid (SSA), moderate semi-arid (MSA), highly semi-arid (HAS), arid (A), absolutely arid (AA), semi-wet (SW), and wet (W). Table 3 shows the distribution of the important scorpion species (in percentage) in the different climates and altitudes, according to the number of presence records for each

species in each climate reported in the earlier studies. Most of the poisonous scorpion species of Iran are scattered in the semi-arid climates (HAS, SSA, MSA). The altitudinal range of distribution is from a minimum of 11 m above sea level for *A. crassicauda* and *M. eupeus* to 2 954 m for *H. zagrosensis*. *H. sauleyi* and *H. zagrosensis* seem to avoid arid climate and prefer semi-wet climate, with a presence record of 22.4% and 36.9%, respectively (Table 3).

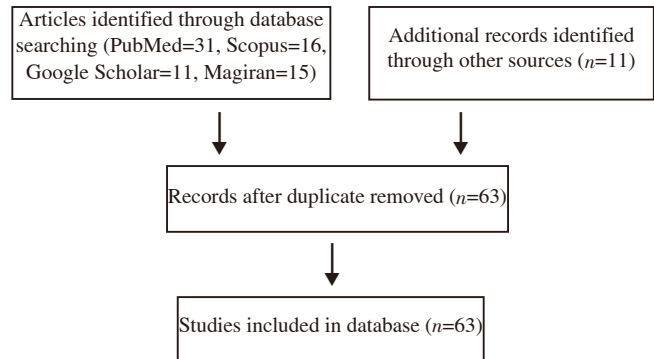


Figure 1. Flowchart of studied documents.

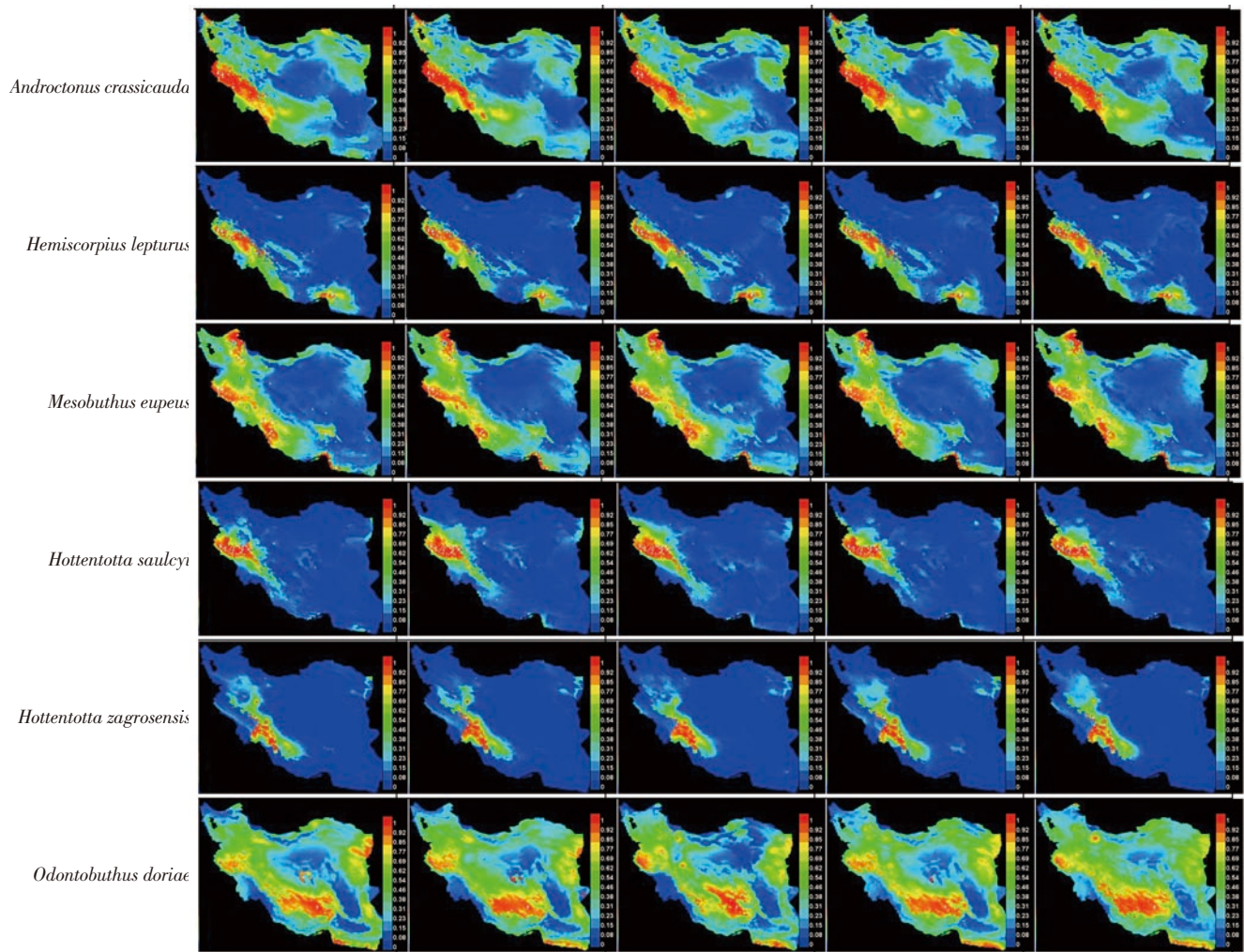


Figure 2. The most appropriate ecological niches for six venomous scorpions of Iran under different climate change scenarios. The red color shows the high environmental suitability for occurrence of scorpion species. So the favourable ecological niches are located in west and south west of Iran for the most venomous species. *Odontobuthus doriae* and *Androctonus crassicauda* have wider distribution and niches in the country.

Table 2. List of scorpions reported from Iran until 2019.

Family	Genus	Species
Buthidae	<i>Androctonus</i>	<i>Androctonus baluchicus</i> (Pocock, 1900)
		<i>Androctonus crassicauda</i> (Olivier, 1807)
		<i>Androctonus finitimus</i> (Pocock, 1897)
	<i>Anomalobuthus</i>	<i>Anomalobuthus talebii</i> (Teruel, Kovarik, Navidpour & Fet, 2014)
	<i>Apistobuthus</i>	<i>Apistobuthus susanae</i> (Lourenco, 1998)
	<i>Buthacus</i>	<i>Buthacus leptochelys</i> (Ehrenberg, 1829)
		<i>Buthacus macrocentrus</i> (Ehrenberg, 1828)
	<i>Compsobuthus</i>	<i>Compsobuthus garyi</i> (Lourenço et Vachon, 2001)
		<i>Compsobuthus jakesi</i> (Kovarik, 2003)
		<i>Compsobuthus kafkai</i> (Kovarik, 2003)
		<i>Compsobuthus kaftani</i> (Kovarik, 2003)
		<i>Compsobuthus matthiesseni</i> (Birula, 1905)
		<i>Compsobuthus persicus</i> (Pocock, 1899)
		<i>Compsobuthus petrioli</i> (Vignoli, 2005)
		<i>Compsobuthus plutenkoi</i> (Kovarik, 2003)
		<i>Compsobuthus rugosulus</i> (Pocock, 1900)
		<i>Compsobuthus sobotniki</i> (Kovarik, 2004)
	<i>Hottentotta</i>	<i>Hottentotta jayakari</i> (Pocock, 1895)
		<i>Hottentotta khuzestanus</i> (Navidpour et al., 2008)
		<i>Hottentotta lorestanus</i> (Navidpour et al., 2010)
		<i>Hottentotta navidpouri</i> (Kovarik, Yagmur & Moradi, 2018)
		<i>Hottentotta saulcyi</i> (Simon, 1880)
		<i>Hottentotta schach</i> (Birula, 1905)
		<i>Hottentotta sistansensis</i> (Kovarik, Yagmur & Moradi, 2018)
	<i>Hottentotta zagrosensis</i> (Kovarik, 1997)	
	<i>Iranobuthus</i>	<i>Iranobuthus kralli</i> (Kovarik 1997)
	<i>Kraepelinia</i>	<i>Kraepelinia palpator</i> (Birula, 1903)
	<i>Liobuthus</i>	<i>Liobuthus kessleri</i> (Birula, 1898)
	<i>Mesobuthus</i>	<i>Mesobuthus agnetis</i> (Werner, 1936)
		<i>Mesobuthus caucasicus intermedius</i> (Nordmann, 1840)
		<i>Mesobuthus caucasicus parthorum</i> (Pocock, 1900)
		<i>Mesobuthus eupeus afghanus</i> (Pocock, 1889)
		<i>Mesobuthus eupeus eupeus</i> (Koch, 1839)
		<i>Mesobuthus eupeus iranus</i> (Birula, 1917)
		<i>Mesobuthus eupeus kermanensis</i> (Birula, 1900)
		<i>Mesobuthus eupeus pachysoma</i> (Birula, 1900)
		<i>Mesobuthus eupeus persicus</i> (Pocock, 1899)
		<i>Mesobuthus eupeus philippovitschi</i> (Birula, 1905)
		<i>Mesobuthus eupeus phillipsi</i> (Pocock, 1889)
		<i>Mesobuthus eupeus thersites</i> (C. L. Koch, 1839)
		<i>Mesobuthus macmahoni</i> (Pocock, 1900)
		<i>Mesobuthus vesiculatus</i> (Pocock, 1899)
		<i>Odontobuthus</i>
	<i>Odontobuthus doriae</i> (Thorell, 1876)	
	<i>Odontobuthus tavighiae</i> (Navidpour, Soleglad, Fet & Kovarik, 2013)	
	<i>Odontobuthus turgari</i> (Mirshamsi, Azghadi, Navidpour, Aliabadian & Kovarik, 2013)	
	<i>Orthochirus</i>	<i>Orthochirus farzanpayi</i> (Vachon et Farzanpay, 1987)
		<i>Orthochirus fuscipes</i> (Pocock, 1900)
		<i>Orthochirus gantenbeini</i> Kovarik, Yagmur, Fet & Hussen, 2019
		<i>Orthochirus goyffoni</i> (Lourenco & Vachon, 1995)
		<i>Orthochirus gruberi</i> (Kovarik & Fet, 2006)
		<i>Orthochirus iranus</i> (Kovarik, 1997)
		<i>Orthochirus mesopotamicus</i> (Birula, 1918)
<i>Orthochirus navidpouri</i> (Kovarik, Yagmur, Fet & Hussen, 2019)		
<i>Orthochirus scrobiculosus dentatus</i> (Birula, 1900)		
<i>Orthochirus scrobiculosus persa</i> (Birula, 1900)		
<i>Orthochirus stockwelli</i> (Lourenco & Vachon, 1995)		
<i>Orthochirus varius</i> (Kovarik, 2004)		
<i>Orthochirus zagrosensis</i> (Kovarik, 2004)		
<i>Polisius</i>		<i>Polisius persicus</i> (Fet et al., 2001)
<i>Razianus</i>		<i>Razianus zarudnyi</i> (Birula, 1903)
<i>Sassanidotus</i>	<i>Sassanidotus gracilis</i> (Birula, 1900)	
	<i>Sassanidotus zarudnyi</i> (Birula, 1903)	
<i>Vachoniolus</i>	<i>Vachoniolus iranus</i> (Navidpour et al. 2008)	
Hemiscorpiidae	<i>Hemiscorpius</i>	<i>Hemiscorpius acanthocercus</i> (Monod & Lourenço, 2005)
		<i>Hemiscorpius enischnochela</i> (Monod & Lourenço, 2005)
		<i>Hemiscorpius gaillardi</i> (Vachon, 1974)
		<i>Hemiscorpius lepturus</i> (Peters, 1861)
		<i>Hemiscorpius persicus</i> (Birula, 1903)
		<i>Hemiscorpius shahii</i> (Kovarik, Navidpour & Soleglad, 2017)
Scorpionidae	<i>Nebo</i>	<i>Nebo henjamicus</i> (Francke, 1980)
	<i>Scorpio</i>	<i>Scorpio maurus kruglovi</i> (Birula, 1910)
		<i>Scorpio maurus townsendi</i> (Linnaeus, 1758)

Table 3. Distribution in different climates of the six dangerous scorpion species and their distributed altitudes in Iran.

Species	Different climates (%)							Altitude [average (range)] (m)
	Slightly semi-arid	Moderate semi-arid	Highly semi-arid	Wet	Semi-wet	Arid	Absolutely arid	
<i>Androctonus crassicauda</i>	15.5*	39.0	21.1	3.3	10.0	4.4	6.7	1 096 (11-2 303)
<i>Hemiscorpius lepturus</i>	18.4	42.2	25.0	0.0	10.5	1.3	2.6	900 (25-2 677)
<i>Mesobotus eupeus</i>	22.5	32.9	22.2	5.6	11.7	0.9	4.2	1 212 (11-2 775)
<i>Hottentota saulcyi</i>	17.6	18.8	30.6	4.7	22.4	0.0	5.9	1 217 (12-2 650)
<i>Hottentotta zagrosensis</i>	5.2	10.5	36.9	10.5	36.9	0.0	0.0	1 452 (150-2 954)
<i>Odontobotus doriae</i>	22.2	51.2	6.7	2.2	4.4	2.2	11.1	1 443 (25-2 456)

*15.5% of *Androctonus crassicauda* are distributed in the slightly semi-arid climate in Iran.

Table 4. The area with more than 60% environmental suitability value for the studied scorpion species in Iran.

Species	Area (km ²) for 60%-100% probability of presence				
	Current	2030s RCP2.6	2030s RCP8.5	2050s RCP2.6	2050s RCP8.5
<i>Androctonus crassicauda</i>	295 120	270 146	294 865	278 085	266 181
<i>Hemiscorpius lepturus</i>	142 717	144 652	150 717	141 796	147 843
<i>Mesobotus eupeus</i>	352 167	350 546	348 265	345 279	373 891
<i>Hottentota saulcyi</i>	107 825	117 347	122 188	104 939	115 558
<i>Hottentotta zagrosensis</i>	163 673	157 729	146 774	164 774	159 536
<i>Odontobotus doriae</i>	566 006	549 949	502 538	556 020	861 885

3.3. Modeling the environmental suitability for the most dangerous scorpion species, under different climate change scenarios in the 2030s and 2050s

For this purpose, six scorpion species: *H. lepturus*, *A. crassicauda*, *M. eupeus*, *H. saulcyi*, *H. zagrosensis*, and *O. doriae* were studied. The results of the MaxEnt model for these species are shown in Figure 2. The red zones represent ecological niches suitable for the activity of the different species of scorpion. Jackknife test showed the environmental variables with the highest gain when used in isolation under each climate scenario. It is projected that *O. doriae*, *A. crassicauda* and *M. eupeus* species would be widely distributed in most parts of the country, whereas the most suitable ecological niches for the other species would be limited to the west and/or southwestern part of Iran. Details of the results obtained from the model are given below.

3.3.1. *Androctonus crassicauda*

This species has been reported in all provinces of Iran, and it has been collected from all the seven climatic zones of the country (Table 3). It is usually found at 11 to 2 303 meters above sea level. The average altitude for this species was estimated at 1 096 m above sea level. The area under ROC curve (AUC) values for training and test data for this scorpion under the different climate change scenarios were as follows: 0.845 and 0.750 under the current climate, 0.833 and 0.763 under RCP2.6 in the 2030s, 0.851 and 0.760 under RCP8.5 in the 2030s, 0.841 and 0.780 under RCP2.6 in the 2050s, and 0.841 and 0.743 under RCP8.5 in the 2050s, respectively.

Figure 2 shows the output of the MaxEnt model for the current climate and two climate change scenarios (RCP2.6 and RCP8.5) in the 2030s and 2050s. Bio19 was the most important environmental variable for predicting the environmental suitability for this species under all scenarios (Figure 3). Considering a cut-off point of 60%, the area (km²) of 61%-100% suitability for *A. crassicauda* was calculated in ArcMap and represented in Table 4 for the two climate change scenarios in the 2030s and 2050s. The results were then compared with that of the current climatic data shown in Figure 2. The results show that the environmental conditions under the current climate are more suitable for the distribution of this species, with a larger area of environmental suitability compared with the 2030s and 2050s. On the other hand, the area of environmental suitability for *A. crassicauda* with more than 60% presence probability would decrease in the 2030s and 2050s, although the decrease seems to be insignificant.

3.3.2. *Hemiscorpius lepturus*

This species has been reported in 18 out of the 31 provinces of Iran. It has been identified in six climatic zones of the country (Table 3). Studies conducted on the fauna of the most important scorpion species of Iran reported that *H. lepturus* was found at 25 to 2 677 meters above sea level. The average altitude for this species was estimated at 900 m above sea level. The AUC values for training and test data for this scorpion under the different climate change scenarios were as follows: 0.944 and 0.849 under the current climate, 0.946 and 0.845 under RCP2.6 in the 2030, 0.942 and 0.835 under RCP8.5 in the 2030s, 0.947 and 0.840 under RCP2.6 in the

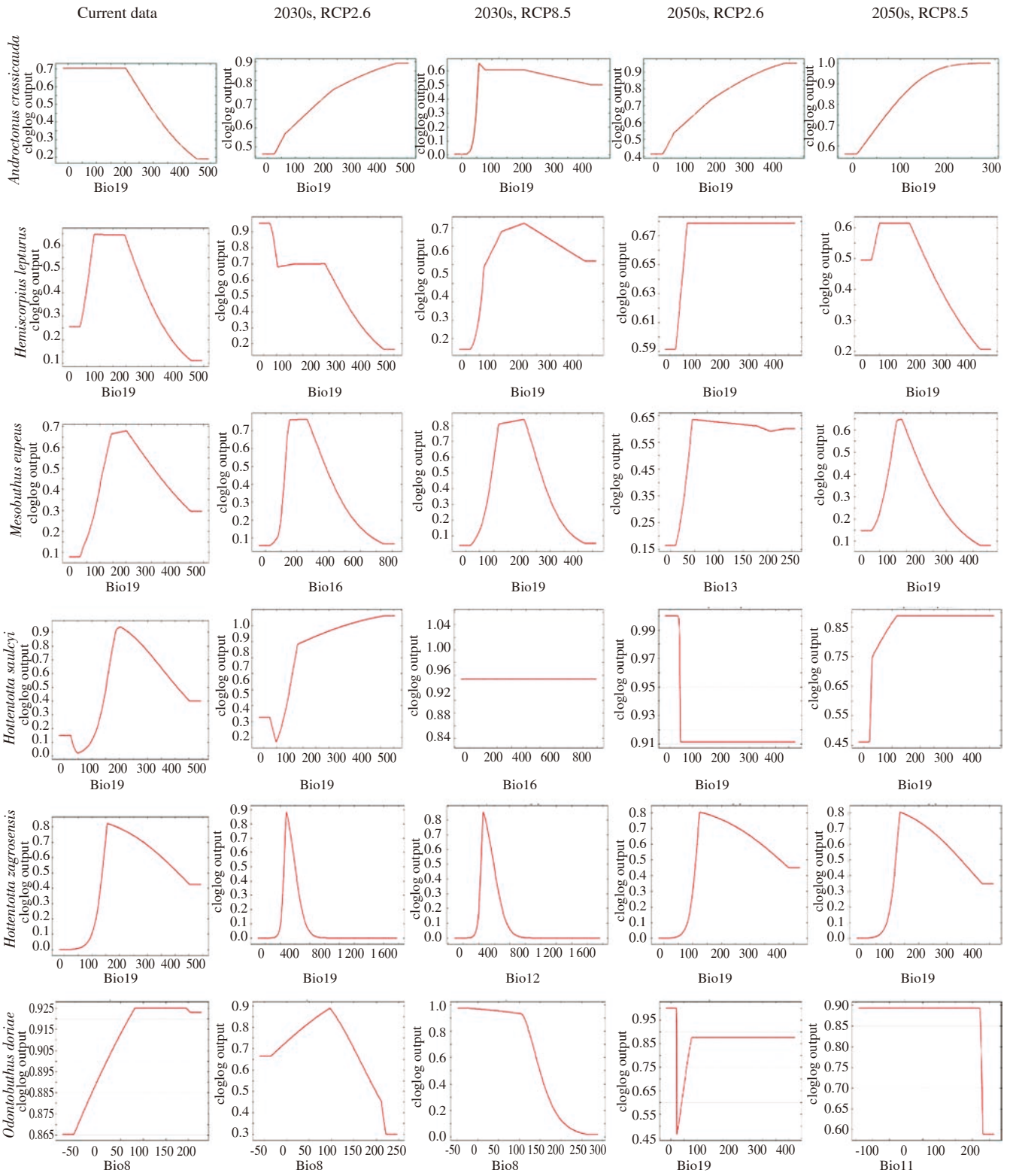


Figure 3. The effective variables on the MaxEnt model for six venomous scorpions of Iran, under different climate change scenarios (response of the six poisonous scorpions to bio19, bio16, bio13, bio12, bio11 and bio8).

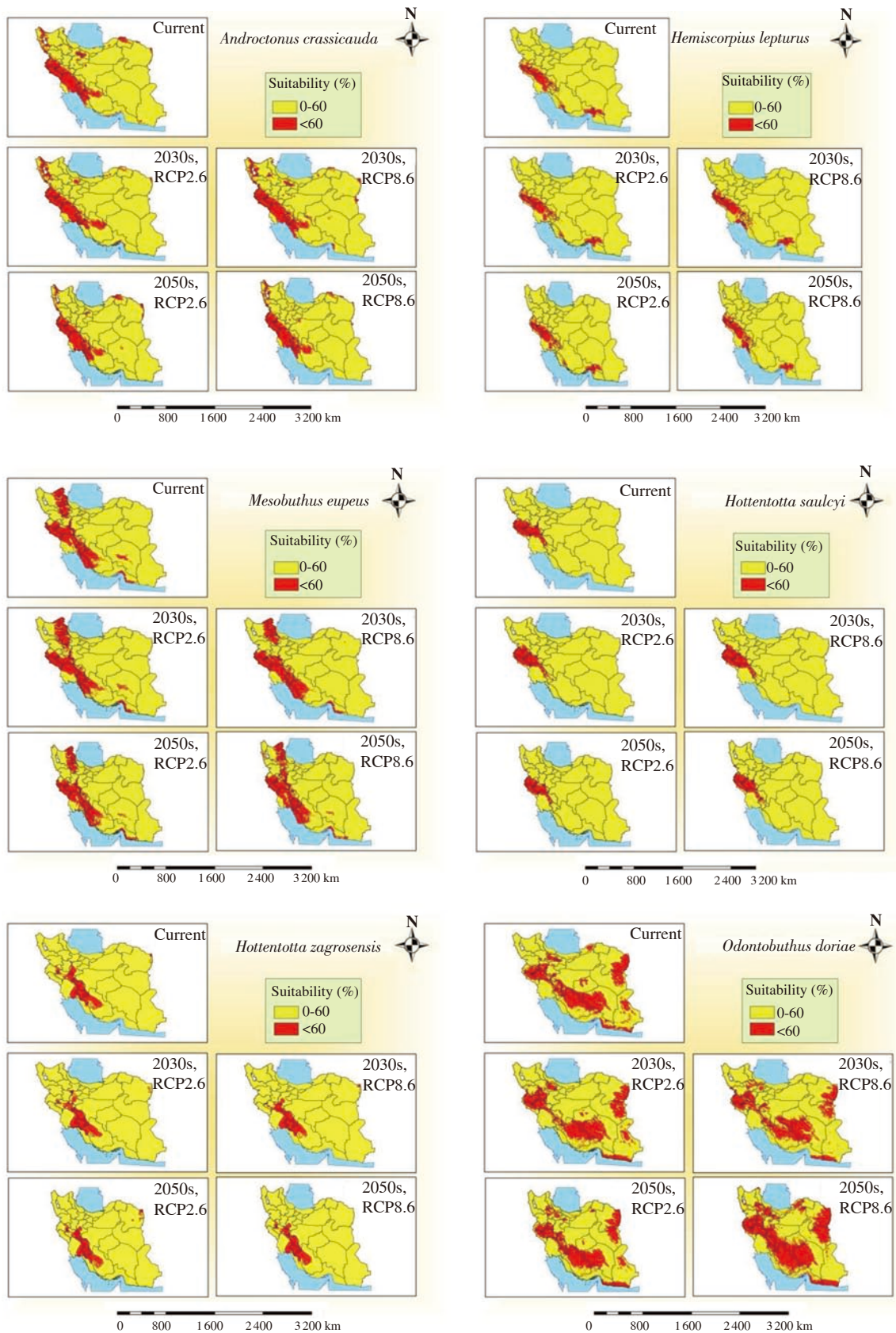


Figure 4. The most appropriate ecological niches for the most important scorpion species of Iran, under different climate change scenarios.

2050s, and 0.944 and 0.850 under RCP8.5 in the 2050s, respectively. Bio19 was the most important environmental variable for predicting the suitable ecological niches for this species (Figure 3). The area of environmental suitability for this species would be the most in the 2030s under RCP8.5 scenario. Compared to the current data, the ecological niche of *H. lepturus* would increase under all scenarios, except in the 2050s under RCP2.6, although this increase seems to be insignificant (Table 4).

3.3.3. *Mesobuthus eupeus*

This scorpion species has also been reported in all the provinces of Iran and it is found in all climatic zones of the country (Table 3). Studies conducted on *M. eupeus* in Iran reported this scorpion species was captured at 11 to 2 775 meters above sea level. The average altitude for this species was estimated at 1 212 m above sea level. The AUC values for training and test data for this scorpion under the different climate change scenarios were as follows: 0.859 and 0.754 in the current climate, 0.857 and 0.762 under RCP2.6 in the 2030s, 0.856 and 0.769 under RCP8.5 in the 2030s, 0.858 and 0.742 under RCP2.6 in the 2050s, and 0.852 and 0.754 under RCP8.5 in the 2050s, respectively. Bio19 was the most important environmental variable for predicting the ecological niches for this species using current climate as well as RCP8.5 in 2030s and 2050s. Bio16 and bio13 were the main predictive variables in the 2030s and 2050s, respectively, under RCP2.6 scenario (Figure 3). The results show that the area of environmental suitability for this species would be the most in the 2050s under RCP8.5 scenario. Compared to the current data, the ecological niche of *M. eupeus* would slightly decrease except for RCP8.5 in the 2050s (Table 4).

3.3.4. *Hottentotta saulcyi*

This scorpion species has been reported in 19 provinces of Iran, and it has been found in six climatic zones of the country (Table 3). The previous studies have reported that *H. saulcyi* was captured at 12 to 2 650 meters above sea level. The average altitude for this species was estimated at 1 217 m above sea level in Iran. The AUC values for training and test data for this species under the different climate change scenarios were as follows: 0.950 and 0.904 in the current climate, 0.935 and 0.880 under RCP2.6 in the 2030s, 0.945 and 0.900 under RCP8.5 in the 2030s, 0.947 and 0.901 under RCP2.6 in the 2050s, and 0.954 and 0.909 under RCP8.5 in the 2050s, respectively. Bio19 was the most important environmental variable for predicting the ecological niches for this species under all scenarios, except for RCP8.5 in 2030s, where bio16 was the main predictive variable (Figure 3). The results show that the area of environmental suitability for this species would be the most in the 2030s under RCP8.5 scenario. Compared to the current data, the ecological niche of *H. saulcyi* would increase under all scenarios, except for RCP2.6 in the 2050s, which showed a slight decrease (Figure 2).

3.3.5. *Hottentotta zagrosensis*

This scorpion species has been reported in six provinces of Iran, and it is found in five out of the 7 climatic zones of the country (Table 3). Studies on the most important scorpion species of Iran reported that *H. zagrosensis* was captured at 150 to 2 954 meters above sea level. The average altitude for this species was estimated at 1 452 m. The AUC values for training and test data for this species under the different climate change scenarios were as follows: 0.974 and 0.910 for the current climate, 0.937 and 0.915 for RCP2.6 in the 2030s, 0.975 and 0.907 for RCP8.5 in the 2030s, 0.970 and 0.903 for RCP2.6 in the 2050s, and 0.970 and 0.904 RCP8.5 in the 2050s. Bio12 was found to be the most important predictive variable in the 2030s (Figure 3). The results show that the area of environmental suitability for this species was the most in the current climatic variables. Compared to the current data, the ecological niche of *H. zagrosensis* would decrease under the climatic data of all scenarios, except for 2050s RCP2.6 (Table 4).

3.3.6. *Odontobuthus doriae*

This species has been identified in 15 provinces of Iran, and it is found in all climatic zones of the country (Table 3). This scorpion was mostly captured at 25 to 2 456 meters above sea level. The average altitude for this species in Iran was estimated at 1 443 m above sea level. The AUC values for training and test data for this scorpion under the different climate change scenarios were as follows: 0.827 and 0.628 for the current climate, 0.833 and 0.643 under RCP2.6 in the 2030s, 0.851 and 0.680 for RCP8.5 in the 2030s, 0.824 and 0.656 for RCP2.6 in the 2050s, and 0.823 and 0.664 for RCP8.5 in the 2050s, respectively. Bio19 was the most important environmental variable for predicting the ecological niches for this species for RCP2.6 in the 2050s, whereas bio8 was the most important predictor for both scenarios in the 2030s as well as the current climatic data. Bio11 was the best predictor for the ecological niches of this species in the 2050s under RCP8.5 scenario (Figure 3). The environmental suitability for this species would be the most in the 2050s under RCP8.5 scenario. Compared to the current data, the ecological niche of *O. doriae* would decrease in the future (Figure 3).

Although the overall area (km²) of >60% suitability would be more or less the same for most of the species under the different climate change scenarios, but the spatial distribution of this species would significantly change in the 2050s under RCP8.5 scenario (Figure 4).

4. Discussion

According to the results of this study, there is a greater number of scorpion species in the southern part of Iran, where the climate is relatively dry. These areas receive more solar radiation than other

parts of the country. Scorpions prefer warmer climates[23], and this can be the main reason for the higher species richness in the southern parts of Iran. According to [38], higher temperatures also shorten generation times and increase maturation rates, thereby accelerating the speciation process of scorpion in the tropics. Another interesting feature of scorpions' diversity and distribution is their successful colonization of arid climates. Unlike most animal groups which have rich biotic representation in the tropics compared to deserts and sandy areas, the most diverse communities of scorpions are found in arid regions. Their remarkable adaptation to such extreme ecosystems involves the ability to tolerate higher temperatures[39]. Metabolic and behavioral adaptations, ability to conserve water for prolonged periods even under very low humid conditions, and living inside burrows deep enough to provide shelter against high ambient temperatures are also other important features that aid their survival in higher temperatures. According to Koch's investigation[3], rainfall, temperature, and possibly species competition are the most important factors influencing scorpion diversity. It seems that scorpion diversity does not depend on vegetation. It is reported that ruggedness and edaphic factors such as soil depth, texture, and nutrient status were strongly correlated with the pattern of scorpion species richness and distribution in arid areas[5]. Regional scorpion species diversity varied from 1 to 13, with most areas having 3 to 7 species, and deserts averaging seven species[40].

The density of scorpion population is highly variable and depends on abiotic and biotic environmental factors. In some studies, temperature, precipitation, wind, and altitude were the most important bioclimatic and environmental factors affecting the diversity of scorpions, and temperature had the highest effect[7,40]. In line with the findings of these research studies, we found that precipitation and temperature are the most important variables affecting the environmental suitability of the six poisonous scorpion species of Iran. Based on climate preference, the scorpion species can be classified into 3 groups: xerophilic (prefer very dry and desert environments), mesophilic (prefer moderately humid environments, rocky areas in the Mediterranean forests, savannah), and hydrophilic (prefer wet tropical forests, caves) scorpions. There is a strong correlation between surface temperature and population density of scorpions. This can be explained by the peak of scorpion sting during the warm months of summer in Iran[6,10]. Many desert scorpions can tolerate temperatures of 45 °C to 50 °C, and this tolerance increases during summer. This interesting adaptive behavior might help the scorpions to adapt to climate change. In the present study, we found that the spatial distribution of the poisonous scorpions of Iran would slightly change but the change will be insignificant. It partly may be due to the potential adaptation of these arthropods to higher temperatures. Also it seems increasing of temperature in tropical areas of southern Iran will not be too much.

Higher altitudes were most favorable for *H. zagrosensis* among all the species. This species mostly avoids arid and absolutely arid climates. The most effective variables on the model for this species were bio 19 and bio 12, both of which represent precipitation. So, it can be concluded that *H. zagrosensis* prefers wet areas, and moisture may be a limiting factor for its distribution. There is no published data on the biology and ecology of this important scorpion. It is recommended that more studies be conducted in this regard.

In the present study, the AUC of the training data for the model for all studied species was more than 0.75, and >0.90 for *H. lepturus*, *H. sauleyi*, and *H. zagrosensis*. This indicates good model prediction for the ecological niches of these scorpion species under all scenarios[41]. There are few studies on ecological niche modeling for scorpions. In a study conducted on ecological niche modeling for a number of scorpion species in Brazil, the most contributed variables in the distribution model of *Tytus serrulatus* were precipitation and tree cover, whereas for *Tytus bahiensis*, temperature and thermal amplitude had the most contribution[42]. In our study, precipitation of coldest quarter of the year (bio 19) was the most important environmental variable for almost all species, except for *O. doriae*, in which mean temperature of the wettest quarter (bio 8) had the most effect on the model for the current climate and in the 2030s. The observed differences may be due to the ecology of the scorpion species as well as the location and number of points used for the modeling.

Other variables like annual precipitation (for *H. zagrosensis*), precipitation of the wettest quarter (for *H. sauleyi* and *M. eupeus*), precipitation of the wettest month (for *M. eupeus* and *A. crassicauda*), and mean temperature of the coldest quarter (for *O. doriae*) had the most effect on the model when used in isolation. Although increase in precipitation to more than 200 mm will decrease the environmental suitability for *A. crassicauda* in the current climatic condition, the model showed a positive correlation between precipitation and environmental suitability in the 2030s and 2050s for this scorpion. It is predicted that rainfall will increase the population density of this deadly scorpion. Regarding the most important predictive variable for the distribution of *H. lepturus* (bio19), the condition is more or less the same for the current climate and in the 2030s and 2050s. In other words, higher precipitation will have a negative effect on this poisonous scorpion. A decrease in rainfall in the coming years might increase the environmental suitability for this scorpion.

The most important predictive variables for *M. eupeus* were bio 19, bio 16, and bio 13. Higher precipitation will reduce the environmental suitability for this species and therefore the risk of stinging by this scorpion. An earlier study on ecological niche modeling for *M. eupeus* and *M. phillipsii* reported that mean temperature of wettest quarter of the year (bio 8) and precipitation of warmest quarter of the year (bio18) were the most important

predictors for these two species, respectively[9]. The model for *H. saulcyi* was similar to that of *A. crassicauda*, such that, precipitation will have a negative effect on the environmental suitability of this species in the current climate and in the 2050s under RCP2.6. However, precipitation will be a positive predictor for this species in the 2030s under RCP2.6 and in the 2050s under RCP8.5. For *H. zagrosensis*, an annual precipitation of up to 300 mm will have a positive effect on its distribution and expand its ecological niches, but higher rainfall will decrease its range of distribution.

Overall, precipitation was the most important predictive variable for 5 out of the 6 scorpion species described above, and temperature seems to be most important predictive variable for the distribution of *O. doriae*. Thus, higher temperature of the wettest quarter and coldest quarter will decrease the environmental suitability of *O. doriae*.

Although the environmental suitability for all the species would change under the two climate change scenarios, the change would be more significant for *O. doriae* under RCP8.5 in the 2050s. These findings can be used as basis for future studies in the areas with the highest environmental suitability for the most dangerous scorpion species to fill the gaps in the ecology of scorpion species in these areas.

Conflict of interest statement

The authors declare no conflict of interest.

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Authors' contributions

J.R. supervised this project. A.A.HB. has prepared the database, analyzed data, modeled and drafted article. M.Sh., Sh. N. and E.J. revised the database. All authors contributed to the final version of the manuscript.

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