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THE EFFECT OF CLIMATE CHANGE ON HABITAT SUITABILITY AND A DISTRIBUTION MODEL OF THE IRANIAN FAT-TAILED GECKO, *EUBLEPHARIS ANGRAMAINYU* ANDERSON AND LEVITON, 1966 (SAURIA: EUBLEPHARIDAE) SINCE THE LAST INTERGLACIAL TO 2050

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Abstract. Surveying the role of climate changes on the species distributions in the past, present and future, and correlating these with changes in distribution ranges have attracted considerable research interest. The leopard geckos of the genus *Eublepharis* Gray, 1827 (family Eublepharidae), as a vicariate group, comprises six valid species distributed from Turkey through the Iranian Plateau to India, of which *E. angramainyu*, *E. macularius* and *E. turcmenicus* occur in Iran. In this study, we modelled the potential distribution areas for *E. angramainyu* and determined the suitable habitats in the past (the last interglacial [LIG] and mid-Holocene [MH]), present (1950–2000), and also predicted four scenarios in the future (2050) by using the maximum entropy approach (MaxEnt). The obtained models indicated very good values of the area under curve (AUC): LIG = 0.996 ± 0.003, MH = 0.996 ± 0.004, contemporary period = 0.995 ± 0.004, and the future = 0.997 ± 0.002. Precipitation of the coldest quarter and precipitation of the warmest quarter were the most important factors shaping the distribution of *E. angramainyu*. As it seems, climatic changes have been responsible for a southward shift in distribution and suitable habitats of *E. angramainyu* from the LIG (~150,000–120,000 years ago) to the future. The representative concentration pathway (RCP) 2.6 scenario model of the future predicted a much more restricted distribution and less suitable habitats due to radiation of the forcing level which reaches a value of around 3.1 W/m^2 by mid-century and returns to 2.6 W/m^2 by 2100.

INTRODUCTION

Global climate change has considerably affected biodiversity, with changes in ecomorphological traits (e.g. shape of limbs), physiological performance (speed and strength), life-history and species distribution ranges (Walther et al. 2002; Hellmann et al. 2008; Visser 2008; López-Alcaide and Macip-Ríos 2011). The Pleistocene glaciations were separated by interglacial periods in the Northern Hemisphere (Ray 1992; Sillero and Carretero 2013). The climate of the last interglacial period (LIG: 150,000–120,000 years ago) was relatively warm or warmer than the present (Kukla et al. 2002; Pickarski 2014). The climate of the mid-Holocene had relatively increased in rainfall along with wetter condition than in the contemporary period in southern and southwest Asia to northern Africa that resulted in both African and Asian monsoons (Texier et al. 2000; Wanner et al. 2008; Jones et al. 2011).

Analysis of species distribution models (SDMs) in the past (last interglacial and mid-Holocene periods) to the present and their changes can help in conservation strategic planning (Karamiani et al. 2018). SDMs predict potential habitat suitability based on evaluating the most important environmental variables for species across a distribution range (Gogol-Prokurat 2011). In other words, SDMs can be used to research the effect of climate changes on the distribution range of species (Thomas et al. 2004).

The genus *Eublepharis* (family Eublepharidae) encompasses six nocturnal lizard species which are distributed from Turkey through the Iranian Plateau to India as follows: south-eastern Turkey, Syria, Iraq, Iran, Pakistan, Afghanistan, Turkmenistan, and north-eastern and central India (Mirza et al. 2014) in a variety of habitats from dry karst topography regions with gypsum deposits and clay-gravel soil to stony foothills (Šmíd et al. 2014). In Iran, the leopard geckos comprise three species with a vicariant distribution: the Iranian fat-tailed gecko, *E. angramainyu* Anderson & Leviton, 1966, which occurs west and southwest of the Zagros Mountains to southwest Kerman Province; *E. macularius* (Blyth, 1854), of which the only known locality is in the eastern region of South Khorasan Province (close to the Afghanistan–Iran border); and *E. turcmenicus* Darevsky, 1977 from the Turkmen borders in North Khorasan and Khorasan

Razavi Provinces, north-eastern Iran (Auer et al. 2008; Šmíd et al. 2014).

In this study, we focus on *E. angramainyu* by using maximum entropy distribution modelling to (1) identify potential areas of distribution during the last interglacial (LIG: ~150,000–120,000 years ago) and mid-Holocene (MH: ~6,000 years ago) periods; (2) describe the contemporary (~1950–2000) distribution, suitable habitats, and understanding of biogeographical patterns; and (3) predict suitable distribution areas for the future (2050).

MATERIALS AND METHODS

Occurrence Data. The study area encompasses the territory of the nocturnal lizard, *E. angramainyu* (Figure 1) from southern Turkey, north-eastern Syria, and Iraq to southern and south-eastern regions of the Iranian Plateau (Anderson 1999; Karamiani and Rastegar-Pouyani 2010; Moradi and Shafiei 2011). The occurrence data of the Iranian specimens were gathered based on a systematic biological survey by walking randomly through the habitat from dusk (~9:00 PM) to dawn (~5:00 AM) (much of the activity time of the species) during several herpetofaunal studies from spring to summer 2010–2019. The exact coordinates were recorded using a Global Positioning System (Garmin GPSmap 60CSx). The distribution data were collected in limestone and gypsum foothills and steppes of the Zagros Mountains from Bazideraz region and Sumar of Kermanshah, Pol-e Dokhtar of Lorestan, Dehloran and Darreh Shahr of Ilam, and Masjed-e-Suleiman and Ramhormoz of Khuzestan Provinces (Figure 2). In other areas (Kohgiluyeh and Boyer-Ahmad and Fars Provinces), *E. angramainyu* specimens were observed between the shrubs and steppes of the Zagros Mountains. The records mentioned in previous studies (e.g. Anderson and Leviton 1966; Leviton et al. 1992; Anderson 1999; Göçmen et al. 2002; Tosunoğlu et al. 2005; Üzüm et al. 2008; Karamiani and Rastegar-Pouyani 2010; Torki 2010; Moradi and Shafiei, 2011; Šmíd et al. 2014) and localities from the Global Biodiversity Information Facility (GBIF: https://www.gbif.org) website (GBIF 2020) were also included. In total, 85 records were gathered and used in this study.

Environmental Data and Analysis. The maximum entropy modelling (MaxEnt, 3.3.3e http://www.cs.princeton.edu/~schapire/MaxEnt) approach was used for the analysis of species geographic distributions under default parameters. All variables were downloaded from the WorldClim website (http://www.worldclim.org) (Table S1). For the modelling of the past distribution (LIG and MH), 19 bioclimatic variables were included at a spatial resolution of 10 km^2 (5 min × 5 min). For

Figure 1. Alive adult specimen of *Eublepharis angramainyu* with a regenerated tail.

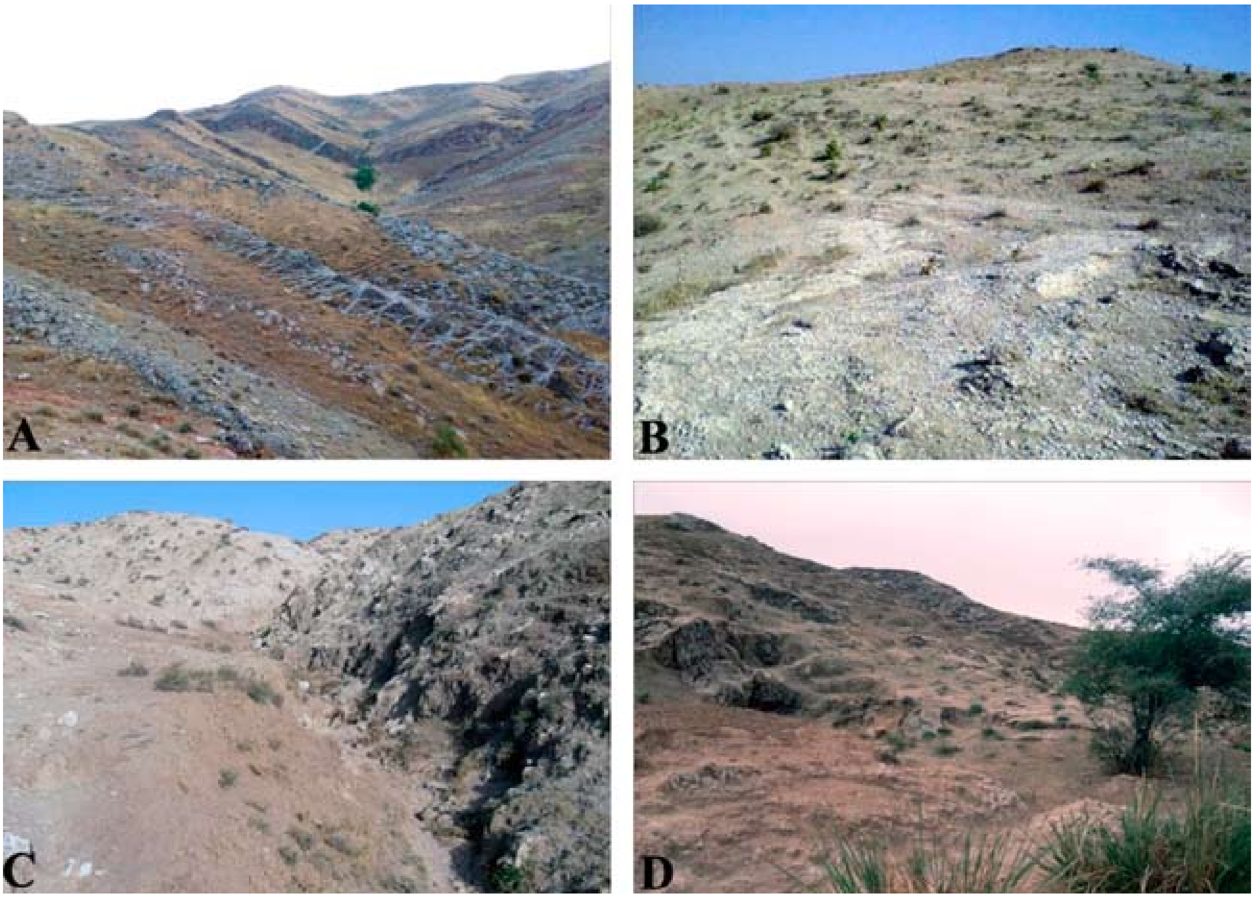

Figure 2. General aspect of habitat of *Eublepharis angramainyu* in Bazideraz Region, Kermanshah Province (A); Pol-e Dokhtar, Lorestan Province (B); Masjed-e-Suleiman (C), and Ramhormoz (D), Khuzestan Province.

the contemporary period (1950–2000), the same 19 bioclimatic variables and two topographical variables with a spatial resolution of 1 km^2 (30 s × 30 s) were used. Finally, for modelling future (2050) distribution the 19 bioclimatic variables were used at a spatial resolution of 1 km^2 (30 s × 30 s) and under four future climatic scenarios in the Middle East (southwest Asia).

The future scenarios are as follows: in the representative concentration pathway RCP 2.6 scenario, greenhouse gas concentration levels are very low under a peak-and-decline scenario; its radiative forcing level first reaches a value of around 3.1 W/m^2 by mid-century (2050) and returns to 2.6 W/m^2 by 2100 (Van Vuuren et al. 2007); in the RCP 4.5 scenario, the total radiative forcing is stabilized before 2100 by employment of a range of technologies and strategies for reducing greenhouse gas emissions (Wise et al. 2009); the RCP 6.0 scenario is a stabilization scenario where the total radiative forcing is stabilized after 2100 without overshoot by employment of a range of technologies and strategies for reducing greenhouse gas emissions (Fujino et al. 2006; Hijioka et al. 2008); and finally the RCP 8.5 scenario is a scenario of increasing greenhouse gas emissions over time, representative of scenarios in the literature that lead to high greenhouse gas concentration levels (Riahi et al. 2007). OpenModeller (V. 1.1.0) (de Souza Muñoz et al. 2011) was used to identify correlations between variables and presence records. We used the IBM SPPS (version 24) for Pearson's correlation coefficient (Elith et al. 2006) to select variables with a correlation lower than 0.75 (Karamiani et al. 2018). We used MaxEnt software with 15 replicates of analysis to obtain the best model for the Iranian fat-tailed gecko. The DIVA-GIS 7.5.0.0 software (available at http://www.diva-gis.org) was utilized for the mean predicted map and a logistic output of presence records with suitability ranging from zero (unsuitable habitat) to one (the best suitable habitat) (Hijmans et al. 2001). General aspect of habitat of *Eublepharis angramainyu* in Bazideraz Region, Kermanshah Province (A); Pol-e Dokhtar, Lorestan Province (B); Masjed-e-Suleiman (C), and Ramhormoz (D), Khuzestan Province.

RESULTS

The distribution of the Iranian fat-tailed gecko *E. angramainyu* was best described by a combination of

Table 1. Relative importance of variables (in percentages) in the last interglacial (LIG, ~120 ka), mid-Holocene (MH, ~6 ka), and contemporary period (1950–2000) used in MaxEnt model for the Iranian fat-tailed gecko, *E. angramainyu*.

Variable	Description of variables	LIG	MH	1950–2000
Bio18	Precipitation of the warmest quarter of the year	52.6	49.2	–
Bio19	Precipitation of the coldest quarter of the year	26.3	32.3	41.5
Bio14	Precipitation of the driest month	13.8	16.3	–
Bio2	Annual daily temperature difference (minimal temperature –maximal temperature)	2.7	0.6	1.7
Bio11	Mean temperature of the coldest quarter of the year	2.4	1.6	27.7
Bio3	Isothermality [(BIO2 / BIO7) × 100]	2.1	–	6.7
Bio15	Seasonality of precipitation (coefficient of variation)	0.1	–	8.4
Bio16	Precipitation of wettest quarter	–	–	3.5
Altitude	Altitude	–	–	5.6
Slope	Slope	–	–	4.8

Table 2. Relative importance of variables (in percentages) in the future (2050) with RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5 scenarios used in MaxEnt model for the Iranian fat-tailed gecko, *E. angramainyu*.

Variable	Description of variables	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Bio18	Precipitation of the warmest quarter of the year	65.8	65.6	66.6	65.9
Bio19	Precipitation of the coldest quarter of the year	31.2	29.2	29.3	31.1
Bio9	Mean temperature of the driest quarter of the year	–	4.4	3.7	–
Bio2	Annual daily temperature difference (minimal temperature – maximal temperature)	1.2	0.5	–	0.9

bioclimatic and geographic variables, that was suggested by a high value of the area under the curve (AUC) values (LIG = 0.996 ± 0.003, MH = 0.996 ± 0.004, contemporary period = 0.995 ± 0.004, and the future = 0.997 ± 0.002). The models exhibited a very good match and closely fitted the presence of the species recorded in the study areas. The contribution of different variables to different time periods is shown in Table 1. In the LIG and MH models, precipitation of the warmest quarter of the year (163–170 mm) explained near half of the variance (49–52.6%); precipitation of the coldest quarter of the year (113–116 mm) and precipitation of the driest month (28–31 mm) explained 40–48.6% of the variance. Therefore, precipitation content was the most important factor for the simulated distribution models during the LIG and MH periods (Figure 3A and B). In the contemporary model, precipitation and mean temperature of the coldest quarter justified 69% of the variance, where mean precipitation was 220 mm with temperature of 6–15 °C (Figure 3C). In future models of the RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5, summation variables of precipitation of the warmest quarter of the year (Bio18) and precipitation of the coldest quarter of the year (Bio19) explained 97%, 94.8%, 95.9%, and 97% of the variance, respectively (Table 2), as *E. angramainyu* only occurred in areas where mean precipitation was 134–175 mm (Figures 4 and 5). The model for *E. angramainyu* predicted the occurrence range of the species in gypsum deposits and mountainsides with elevation of 27 to 2099 m above sea level (a.s.l.) and slopes to 89°.

DISCUSSION

Results of the present study verify the known distribution of the Iranian fat-tailed gecko based on climatic conditions. The western and south-western regions of the Iranian Plateau, north-eastern Iraq, and southern Turkey to the Levant had a wide variety of area suitability for the presence of *E. angramainyu* during four time periods: LIG, MH, contemporary, and future. The only exception is a record (one male specimen) from the southwest of Kerman Province, south-eastern Iran by Moradi and Shafiei (2011) in rocky desert and arid grasslands habitat.

In western and south-western regions of the Iranian Plateau, *E. angramainyu* occurs in karst features (cavities, subsidence areas and sinkholes) as well as in gypsum hills (e.g. Qasr-e Shirin and Sarpol-e Zahab in Kermanshah Province; Dehloran, and Dare Shahr in Ilam Province; Pol-e Dokhtar in Lorestan Province; Masjed-e-Suleiman and Ramhormoz in Khuzestan Province; Nourabad Mamasani in Fars Province (Šmíd et al. 2014)). In conformity with the results, Boulenger (1885) recorded a specimen from the ruins of Nineveh, in the upper Mesopotamian Plain (Leviton et al. 1992), and also Anderson (1999) mentioned two localities (a specimen from near the village of Chalga, south of Chem-che, Kirkuk Province, and another from Khanaqain area, Diyala Province) in Iraq. The species is also recorded from Al-Khatonia in Al-Hasakah Province, north-eastern Syria (Martens and Kock 1991).

Also, the Iranian fat-tailed gecko occurs on the ground enriched by clay-limestone in southern Turkey (Göçmen et al. 2002). The results showed that the distribution of the species is restricted by different climatic factors. Model distribution ranges during the MH to 1950–2000 indicated a gradual decline of habitat suitability in Cyprus and the Levant to Iran. During summer, the rainfall fluctuations over the regions show a clear decrease from the MH to contemporary time that can be elucidated by the changes in solar insolation due to

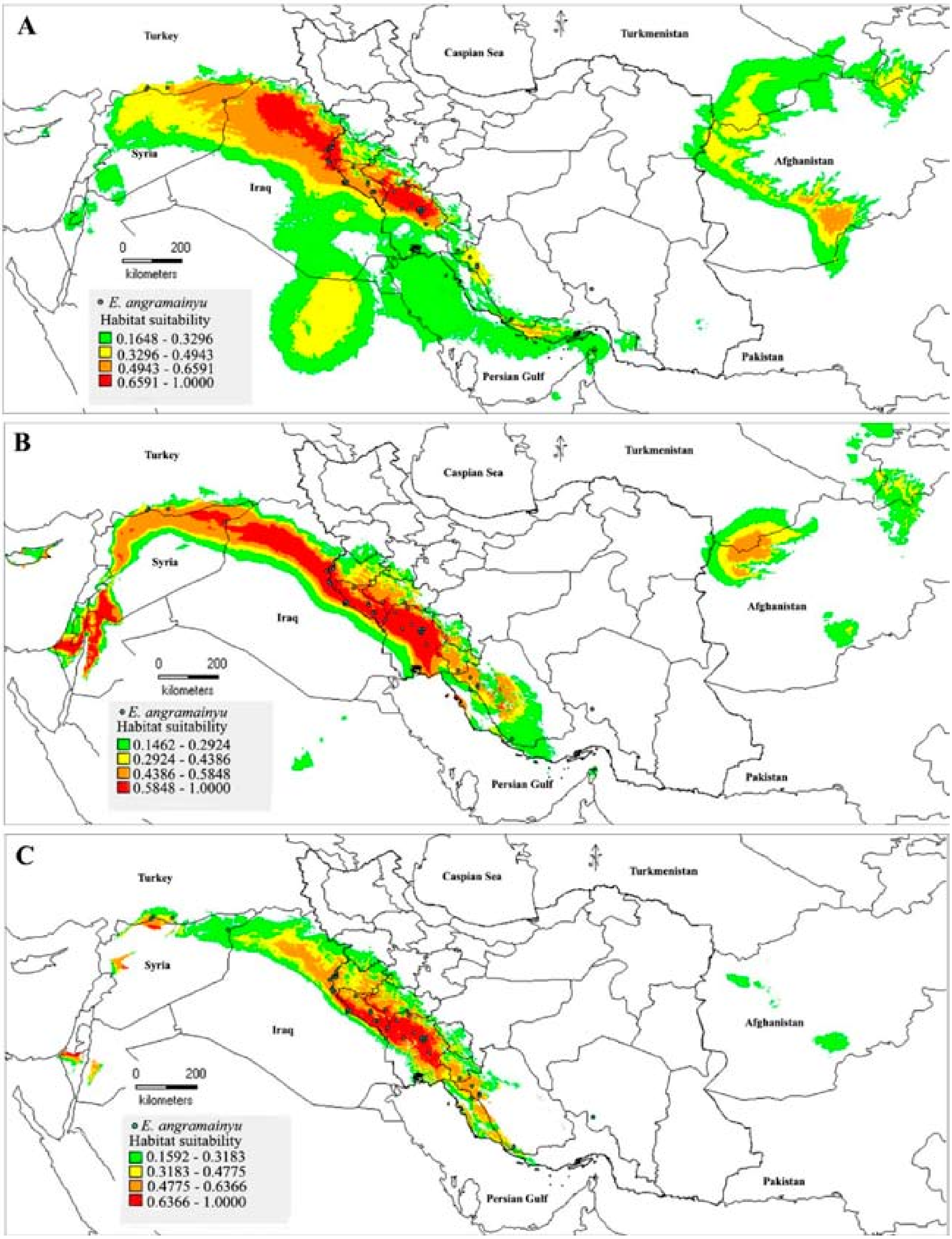

Figure 3. Distribution map of *Eublepharis angramainyu* and its potential distribution pattern during: A) the last interglacial (~120 ka), B) the mid-Holocene (~6 ka), and C) contemporary period (1950–2000).

the varying orbital forcing (Fallah et al. 2017). Model distribution ranges of 2050 with each scenario (RCP: 2.6, 4.5, 6.0, 8.5) predicated more habitat suitability than before, probably due to precipitation during the Sudan monsoon. The LIG and MH distribution models were influenced by precipitation of the warmest quarter (52.6%; 49.2%), precipitation of the coldest quarter (26.3%; 32.3%), and the driest month (13.8%; 16.3%). As it seems based on the results, due to the relationship between precipitation and influx water in karsts and cavities of gypsum deposit, we think that precipitation, especially during summer, is the most effective factor determining the habitat suitability for *E. angramainyu*. In addition to habitat change, decreasing connectivity between suitable habitats and consequent reduction of gene flow among populations leads to an increased extinction risk (Fischer and Lindenmayer 2007; Ferraz et al. 2007). Although there was a relatively good habitat connectivity within landscapes in the past and contemporary climatic models, an overall decrease is expected across *E. angramainyu* distribution range due to climate change. Four patterns are predicted due to climate changes in our modelling. First, a suitable habitat is expected to almost disappear in the areas of climate change, such as in Ilam Province. Second, the size of suitable habitats in large cities will decrease, such as in Khuzestan Province. Third, some increases in suitable habitats are predicted in Iran (Bohsher, Fars, Kohgiluyeh and Boyer-Ahmad, Chaharmahal and Bakhtiari, Lorestan, and Kermanshah Provinces) as well as in Iraq (Diyala, Salah al-Din, Kirkuk, Nineveh Provinces) (Figure 5). Therefore, depending on the region, climatic changes can cause disappearance/decrease as well as partial expansion of suitable habitats (Parmesan 2006; Bonino et al. 2015; Kim et al. 2020). These latter regions might function as potential refuges for conservation of the species under changing climate in the future (Kim et al. 2020).

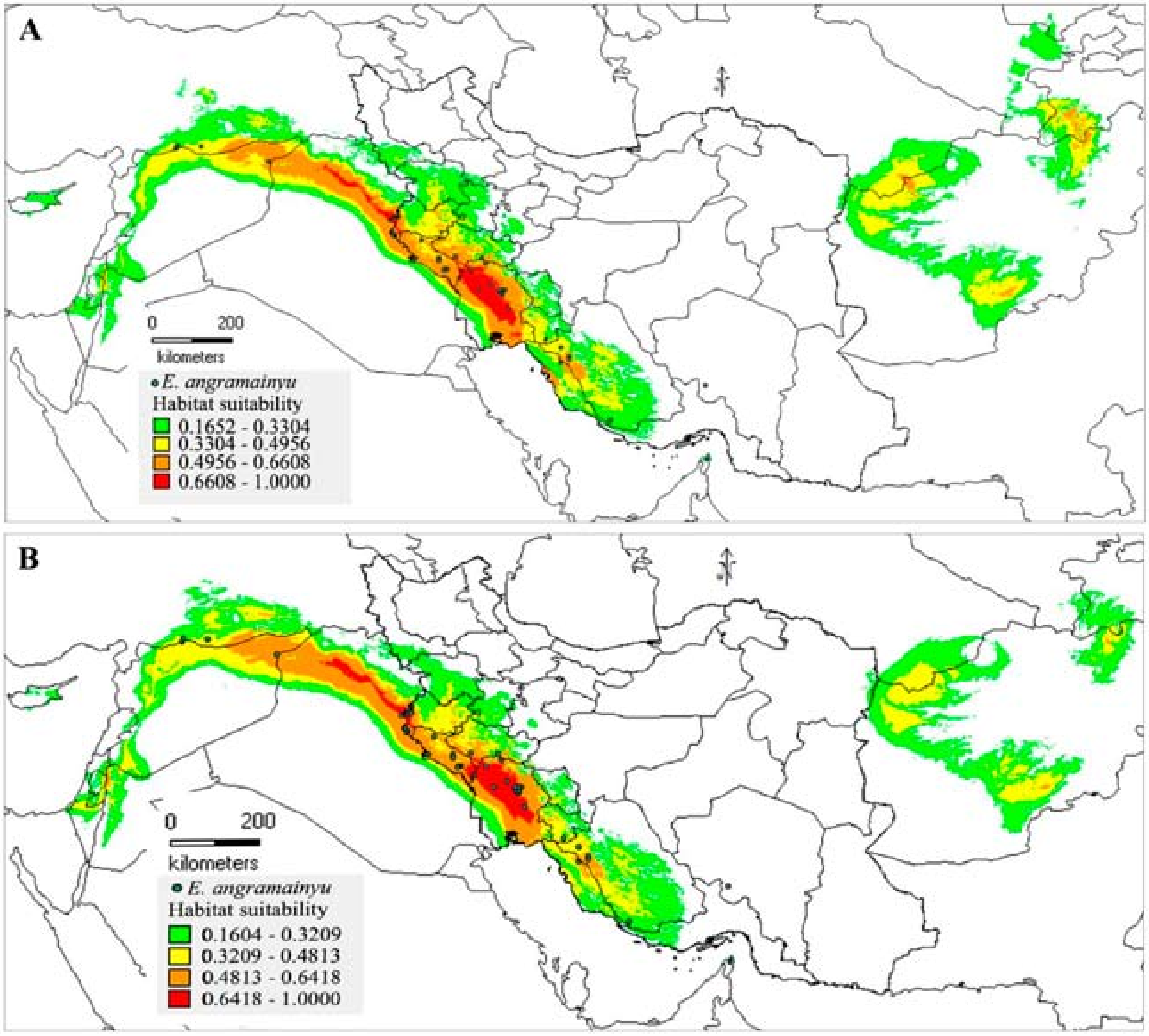

Figure 4. Predicted distribution of *Eublepharis angramainyu* during 2050: A) scenario RCP 2.6, B) scenario RCP 4.5.

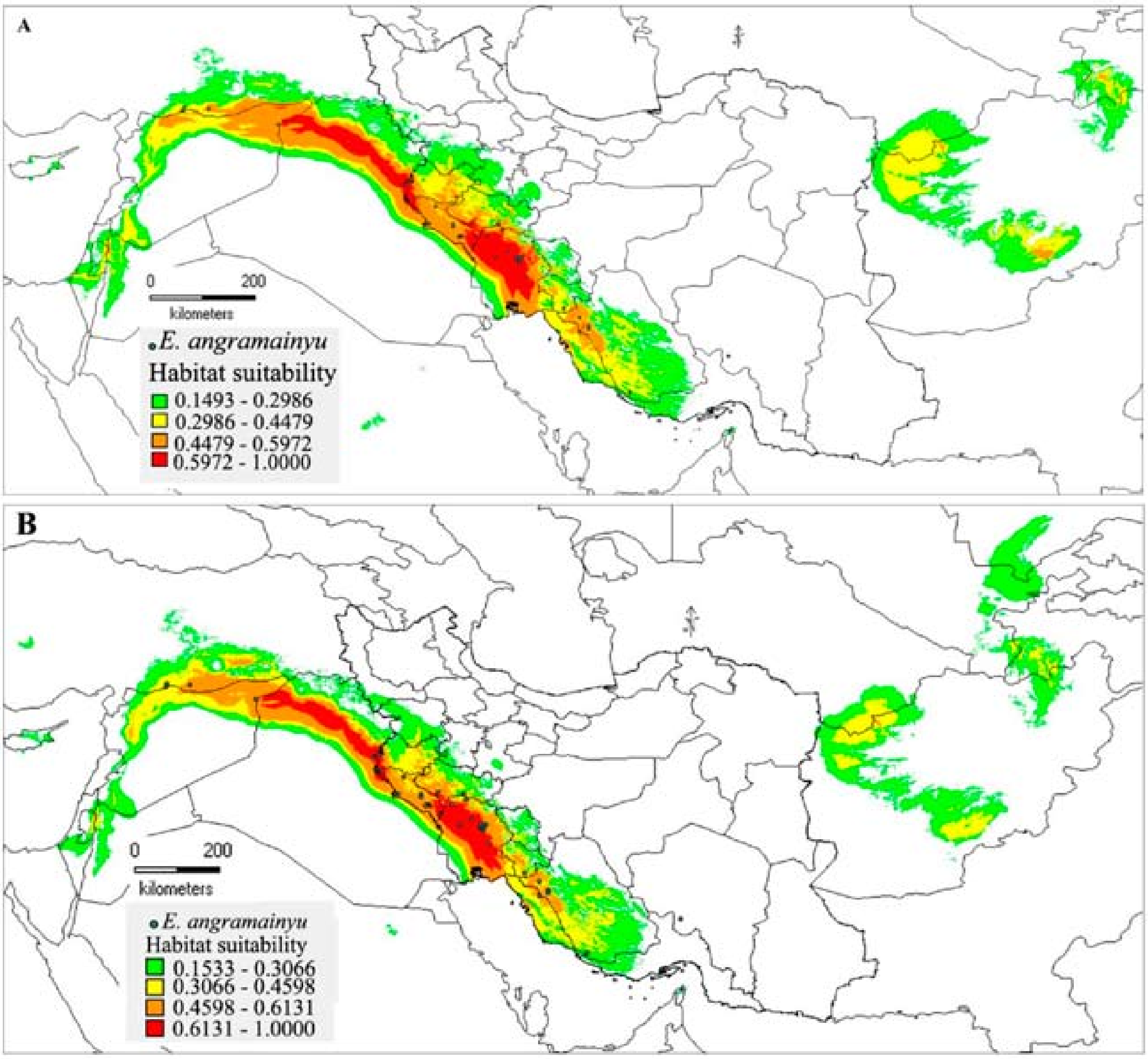

Figure 5. Predicted distribution of *Eublepharis angramainyu* during 2050: A) scenario RCP 6.0, B) scenario RCP 8.5.

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SUPPLEMENTARY MATERIAL

Table S1. Climatic and landscape variables used to elaborate the models (www.worldclim.org).

Characters	Definition
Altitude	Altitude
BIO1	Annual mean temperature
BIO2	Mean diurnal range [mean of monthly (max temp – min temp)]
BIO3	Isothermality [(BIO2 / BIO7) * 100]
BIO4	Temperature seasonality (standard deviation * 100)
BIO5	Maximum temperature of the warmest month
BIO6	Minimum temperature of the coldest month
BIO7	Temperature annual range (BIO5 – BIO6)
BIO8	Mean temperature of the wettest quarter of the year
BIO9	Mean temperature of the driest quarter of the year
BIO10	Mean temperature of the warmest quarter of the year
BIO11	Mean temperature of the coldest quarter of the year
BIO12	Annual precipitation
BIO13	Precipitation of the wettest month
BIO14	Precipitation of the driest month
BIO15	Precipitation seasonality (standard deviation / mean)
BIO16	Precipitation of the wettest quarter of the year
BIO17	Precipitation of the driest quarter of the year
BIO18	Precipitation of the warmest quarter of the year
BIO19	Precipitation of the coldest quarter of the year
Slope	Slope