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Ecological Niche Modelling of the Genus *Anatololacerta* under Past, Historical and Future Bioclimatic Conditions

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Anatolia has played an important role in the speciation of many species. Global climatic changes affect the distribution of many reptiles in different ways, including their range expansion or habitat loss. In this study, we focused on the genus *Anatololacerta* which inhabits Anatolia and some Greek islands. In total, 150 literature records and 20 items of observation data were analysed with the maximum entropy method (MaxEnt) for the last glacial maximum (LGM), as well as historical (1970-2000) and future (2081-2100; RCP 4.5) bioclimatic conditions. According to our model, the distribution ranges in the future conditions for *A. danfordi*, *A. finikensis* and *A. ibrahimi* were more extensive than for the historical conditions. However, *A. anatolica* and *A. pelasgiana* may experience a potential habitat loss in the future. Although physical barriers were obstacles in the LGM and historical records, these barriers may be overcome after the climatic changes taking place in the near future.

Key words: Climate change, Anatolia, Lacertidae, MaxEnt, LGM, RCP 4.5.

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Reptiles have been widely distributed throughout the world in a time period ranging from the Palaeozoic era to the present day (REISZ *et al.* 2011; BÖHM *et al.* 2013). Although reptiles play important roles in nature, nearly one in five species of reptiles are currently at risk of extinction (BÖHM *et al.* 2013). The main risks for reptile extinction are habitat loss and degradation, pollution, invasive species, disease, climate change and harvesting from nature by the pet trade (GIBBONS *et al.* 2000; MARSHALL *et al.* 2020). Terrestrial reptiles have a narrower distributional range and are affected by ecological changes due to being ectotherms (BÖHM *et al.* 2013; CARRANZA *et al.* 2018; ALATAWI *et al.* 2020). The most dramatic scenario for reptiles related to climatic change is their extinction due to habitat changes, which are linked to precipitation and temperature changes (GIBBONS *et al.* 2000; ARAUJO *et al.* 2006; BÖHM *et al.* 2013). ARAUJO *et al.* (2006) reported that climate cooling would be more dangerous for reptile species than global warming. Since climate change also affects the sex determination of some species of turtles and crocodiles, male turtles may become extinct in certain future scenarios (JANZEN 1994; GONZALEZ *et al.* 2019). In the future climate scenario, the distributions of most species may change, along with reductions and increases in their range or shifts in the latitudes and elevations (GOMEZ-RUIZ & LACHER Jr. 2019).

Members of the Lacertidae family are widely distributed in Eurasia and Africa, and the family is represented by around 340 species (ARNOLD *et al.* 2007; GARCIA-PORTA *et al.* 2019). Lacertids live in numerous environmental conditions ranging from deserts to rainforests and from sea level to high mountains (GARCIA-PORTA *et al.* 2019). The Lacertidae family has been divided into two subfamilies – Lacertinae and Gallotiinae – as a result of DNA sequencing (ARNOLD *et al.* 2007). The Lacertinae subfamily is further split into two monophyletic tribes: Lacertini are distributed in Europe, Northwest Africa and Southwest and East Asia; while Eremiadini are present in Africa and in Southwest and Central Asia (ARNOLD *et al.* 2007).

Members of the genus *Anatololacerta* are distributed throughout Turkey and the Greek islands (Samos, Ikaria, Rhodes and Psomis) (ARNOLD *et al.* 2007; BELLATI *et al.* 2015; KARAKASI *et al.* 2021). ARNOLD *et al.* (2007) reported that the Western and Southern Anatolian *Lacerta* group should be defined as a new genus named *Anatololacerta.* This genus, which lives in Anatolia and the Aegean islands of Samos, Ikaria and Rhodes, was represented by three species at that time: *A. anatolica* (Werner, 1900)*, A. danfordi* (Günther, 1876) and *A. oertzeni.* The subspecies taxonomy of this genus was controversial and included nine morphological subspecies (*A. anatolica, A. a. aegaea, A. oertzeni, A. o. budaki, A. o. ibrahimi, A. o. finikensis, A. o. pelasgiana, A. o. quandtaylori, A. danfordi and A. d. bileki*) (BELLATI *et al.* 2015; CANDAN *et al.* 2016). BELLATI *et al.* (2015) conducted a molecular study about this genus and reported that this genus was represented by four species in Anatolia (*A. anatolica, A. pelasgiana* (Mertens, 1959), *A. budaki* and *A. danfordi*). In this study, *A. oertzeni* was demoted to the subspecies level and two of the subspecies of *A. oertzeni* (*A. o. pelasgiana* and *A. o. budaki*) were recognised as having a species rank (BELLATI *et al.* 2015). CANDAN *et al.* (2016) reported that *A. oertzeni* and *A. danfordi* each have two well-supported lineages. The last revision of this genus was conducted by KARAKASI *et al.* (2021) who found five well-supported parapatric species in the genus *Anatololacerta.* However, *A. anatolica*, *A. pelasgiana* and *A. danfordi* still remain distinct species, as in BELLATI *et al.* (2015), while *A. ibrahimi* (Eiselt & Schmidtler, 1987) and *A. finikensis* (Eiselt & Schmidtler, 1987) were identified as separate species (KARAKASI *et al.* 2021).

The niche for one species includes both biotic (predations, competition, dispersal limitation, etc.) and abiotic (climatic, environmental, etc.) factors (STIGALL 2012; HEIDARA 2021). Ecological niche modelling (ENM) creates a predicted distribution map by using the climatic and geographical conditions based on known locality records (GÜL *et al.* 2015). Under the niche conservatism theory, a species preserves its ecological niche parameters following environmental changes, and such a species overcomes those environmental changes by shifting their preferred habitat laterally if they have the dispersal potential (STIGALL 2012; TOK *et al.* 2016). If the species does not have the ability for a dispersal potential, they will lose their range and may become extinct (ARAUJO *et al.* 2006; TOK *et al.* 2016). The prediction of distributions is more significant in terms of evolutionary biology due to the resulting gene flow (PRÖHL *et al.* 2010), and for ecology and conservation biology due to the shifting between habitats (TOK *et al.* 2016).

The aim of this study was to determine the possible distribution of the *Anatololacerta* genus and its related species by ecological niche modelling methods under the last glacial maximum, historical and future conditions.

Material and Methods

All the occurrence data for the species belonging to *Anatololacerta* was obtained from the literature (150 records from: ANDREN & NILSON 1976; MULDER 1995; WINDEN *et al.* 1997; ERDOĞAN *et al.* 2002; ÖZDEMİR & BARAN 2002; KETE *et al.* 2005; AFSAR & TOK 2011; UYSAL & TOSUNOĞLU 2012; CİHAN & TOK 2014; ESER & ERİŞMİŞ 2014; ÖZCAN & ÜZÜM 2014; TOK & ÇİÇEK 2014; BELLATI *et al.* 2015; EGE *et al.* 2015; KUCHARZEWSKI 2015, 2016; KUMLUTAŞ *et al.* 2015; CANDAN *et al.* 2016; MERT & KIRAÇ 2017; SARIKAYA *et al.* 2017; ARSLAN *et al.* 2018; GİDİŞ & BAŞKALE 2020; YILDIRIMHAN *et al.* 2020; KARAKASI *et al.* 2021; ÖZKAN & BÜLBÜL 2021) and from personal observations (20 records). The number of localities used by each species was as follows: 40 localities for *A. anatolica*; 27 localities for *A. danfordi*; 21 localities for *A. finikensis*; 49 localities for *A. ibrahimi*; and 33 localities for *A. pelasgiana.* Geographical coordinates and references are given in the Supplementary Material. If the coordinates are stated in the article, they were used directly for the analysis; however, other coordinates were determined and checked using Google Earth Pro version 7.3.2.

Nineteen bioclimatic variables were downloaded from WorldClim vers. 1.4 for the past climatic conditions [Last Glacial Maximum (LGM)] and vers. 2.1 for the historical (1970-2000) and future (2081-2100) conditions, with a spatial resolution of 2.5 arc-minutes (approximately 5 km^2) (HIJMANS *et al.* 2005; FICK & HIJMANS 2017). Some of the bioclimatic variables seemed to be redundant (GÜL *et al.* 2015) and the correlation matrix was calculated with the Niche ToolBox web application (OSORIO-OLVERA *et al.* 2020). Pearson correlation coefficients higher than 0.75 were accepted as correlated variables, and these variables were excluded from the analysis. Six environmental variables [bio1 = Annual Mean Temperature; bio2 = Mean Diurnal Range (mean of the monthly (max temp - min temp)); bio3 = Isothermality (BIO2/BIO7) (×100); bio4 = Temperature Seasonality (standard deviation × 100); bio12 = Annual Precipitation; and bio14 = Precipitation of the Driest Month] remained in the analysis.

For the past climate conditions, the LGM (nearly 21,000 years ago) at a spatial resolution of 2.5 arc-minutes was used. Data on the LGM climate was generated with the MIROC-ESM model (Model for Interdisciplinary Research on Climate) (HIJMANS *et al.* 2005). For the future climate conditions (2081-2100 years), the MIROC6 (TATEBE *et al.* 2019) model with presentative conservation pathways (THOMSON *et al.* 2011) predicting climate change emission scenarios was used with a spatial resolution of 2.5 arc-minutes.

The variables selected after the correlation analysis were imported into Maxent vers. 3.4.1 (PHILLIPS *et al.* 2006; PHILLIPS & DUDIK 2008; https://biodiversity-informatics.amnh.org/open_source/maxent/), which is an effective modelling tool for ecological studies (GÜL *et al.* 2018). This program was also used to investigate the geographical distributions of species and the climatic limitations on their distribution (GÜL *et al.* 2018). The Maxent algorithm estimates (0 is the lowest and 1 is the highest probability) the habitat's suitability with a maximum entropy distribution by using locality point data (GÜL *et al.* 2015; ALATAWI *et al.* 2020). The features for this study were organised as 20 subsampled replicates, with 5000 iterations and *cloglog* outputs. We used Area Under the Curve (AUC) for an estimation of the significance of the model, calculated from the Receiver Operating Curve (ROC) (ALATAWI *et al.* 2020). The predicted distribution maps obtained from Maxent were imported into ArcGIS vers. 10.3.1 for a visualisation.

Results

Anatololacerta anatolica

The areas predicted to be suitable for *A. anatolica* had a high AUC of 0.944±0.051 for the LGM, 0.945±0.044 for the historical and 0.943±0.038 for the future bioclimatic conditions (Figure 1, Table 1). There was only one suitable place, situated in the centre of the Taurus Mountains. Other parts of Anatolia were unsuitable during the LGM.

West of Amanos Mountain, east of the Antalya Gulf, Muğla Province, Gediz Basin, the Büyük Menderes basins, Gallipoli and south of the Marmara Sea were seen as suitable places for the historical bioclimatic conditions, while the rest of Anatolia was determined to be unsuitable.

As can be seen in the future climatic conditions, the distribution range was narrower than under the historical conditions. In the future, it is expected that the possible distribution of *A. anatolica* will include only the area south of the Marmara Region, especially around Uludağ Mountain.

Anatololacerta danfordi

The areas predicted to be suitable for *A. danfordi* had a high AUC of 0.917±0.123 for the LGM, 0.912±0.145 for the historical and 0.906±0.141 for the future bioclimatic conditions (Figure 2, Table 1). Southeast Anatolia east of Amanos Mountain, south of the Middle Taurus Mountain and İzmir Province were determined to be suitable places for this species, while Thrace, the Black Sea Region and west of Central Anatolia were identified to be unsuitable.

In the historical climatic conditions, the distribution model showed that the Adana and Mersin Region, Antalya and the Aegean Region were suitable places, while Eastern Anatolia, Thrace and the Black Sea Region were identified as unsuitable places. When the distributions between the LGM and historical predictions are compared, the suitable places drift from the east to the west of Anatolia for *A. danfordi.*

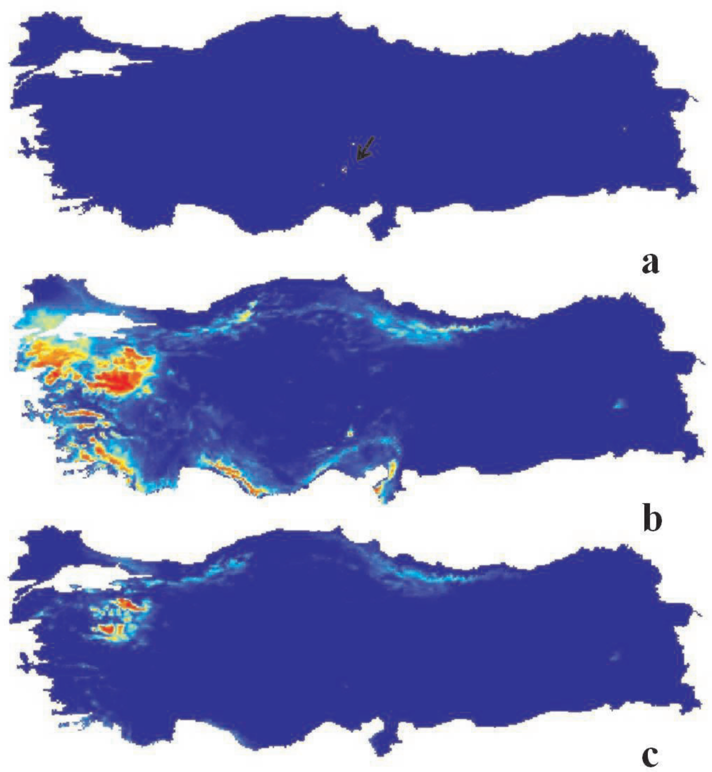

Fig. 1. Habitat suitability for *Anatololacerta anatolica* in Turkey. The arrow shows the only suitable place on the map. a) LGM; b) historical; and c) future bioclimatic conditions. Warm colours refer to highly suitable places on the map.

Table 1

Percent contributions (PC) and permutation importance (PI) values of the genus *Anatololacerta* for LGM, historical and future bioclimatic conditions

Species	Historical time	Variables											
		Bio1		Bio2		Bio3		Bio4		Bio12		Bio14	
		PC	PI	PC	PI	PC	PI	PC	PI	PC	PI	PC	PI
A. anatolica	LGM	8.1	8.7	0.5	0	0	0	45.5	63.3	30.6	15.7	15.3	12.3
	Historical	6.8	6.2	0.5	0.1	0	0	46.6	56.7	33.2	19.0	12.9	18.0
	Future	7.4	7.3	0.5	0	0	0	45.5	66.9	31.9	18.7	14.7	7.1
A. danfordi	LGM	0.3	0.3	0.6	7.9	16.5	8.5	31.2	39.6	9.0	1.7	42.4	42.0
	Historical	0.2	0.4	1.3	5.2	16.0	13.7	29.9	33.7	8.5	2.3	44.1	40.7
	Future	0.1	0.2	0.9	5.4	16.3	9.1	30.5	40.5	8.9	1.9	43.3	42.8
A. finikensis	LGM	32.0	14.0	7.5	17.2	43.6	18.4	12.2	12.2	1.5	0	3.3	38.2
	Historical	27.8	21.2	9.3	18.3	47.1	8.4	11.0	14.8	1.2	0	3.6	37.3
	Future	30.2	11.3	8.5	27.6	46.0	21.0	10.4	12.8	1.6	0	3.4	27.4
A. ibrahimi	LGM	3.5	1.6	4.4	0.9	4.0	2.5	43.0	34.6	19.2	25.1	26.0	35.3
	Historical	3.2	2.8	4.2	4.6	3.9	3.9	42.5	38.4	19.0	18.0	27.2	32.3
	Future	2.5	2.1	3.7	0.7	3.4	2.6	44.1	32.8	19.5	20.3	26.8	41.5
A. pelasgiana	LGM	26.9	1.5	0	0	20.5	30.1	27.4	19.2	12.7	29.1	12.5	20.1
	Historical	27.5	1.2	0	0	19.9	28.3	28.1	18.2	12.0	24.2	12.5	28.2
	Future	27.9	1.3	0	0	18.7	22.8	29.8	20.9	11.4	29.2	12.2	25.9

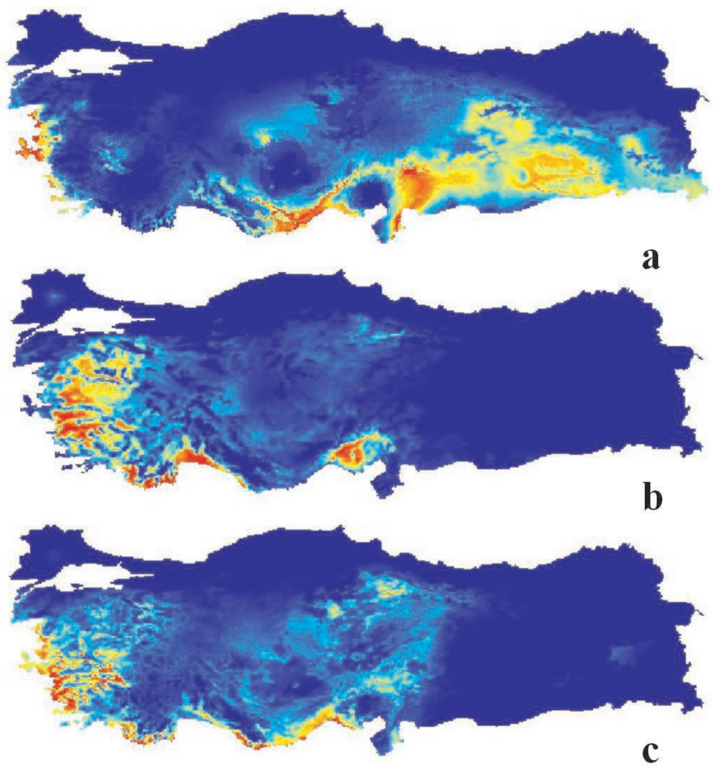

Fig. 2. Habitat suitability for *Anatololacerta danfordi* in Turkey. a) LGM; b) historical; and c) future bioclimatic conditions. Warm colours refer to highly suitable places on the map.

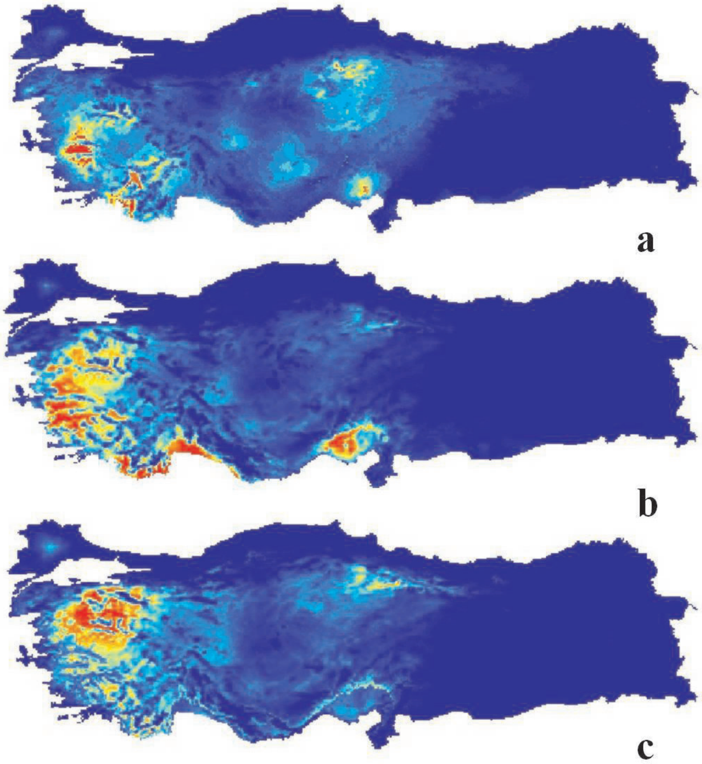

Fig. 3. Habitat suitability for *Anatololacerta finikensis* in Turkey. a) LGM; b) historical; and c) future bioclimatic conditions. Warm colours refer to highly suitable places on the map.

According to the future bioclimatic conditions, the Aegean Region, Central Anatolia and the Mediterranean Region were identified as suitable places, while Thrace, the Black Sea Region, Southeast Anatolia and Northeast Anatolia were determined to be unsuitable places. The distribution model for the future climatic conditions showed that suitable places will be more extensive than in the historical climatic conditions.

Anatololacerta finikensis

The mean AUC values for *A. finikensis* for the LGM, historical and future climatic conditions were calculated as 0.955±0.044, 0.958±0.040 and 0.959±0.041, respectively (Figure 3, Table 1). While the Aegean Region, Adana and Sivas were identified as suitable places for this species, the rest of Anatolia was determined to be unsuitable.

According to the historical climatic conditions, the predicted distribution models showed that the LGM and historical climatic conditions were mainly similar, where the Cilicia Region and Antalya appeared to be suitable. The distribution of *A. finikensis* in the historical climatic conditions was more extensive than in the LGM.

The distribution model for the future conditions was mainly similar to that for the historical climatic conditions, but Central Anatolia appeared to be more suitable than in the historical climatic conditions. The Cilicia Region was also determined to be unsuitable under the future conditions.

Anatololacerta ibrahimi

The calculated mean AUC values for *A. ibrahimi* for the LGM, historical and future climatic conditions were 0.914±0.063, 0.927±0.052 and 0.921±0.043, respectively (Figure 4, Table 1). All parts of Anatolia seemed to be unsuitable for *A. ibrahimi* under the LGM bioclimatic conditions.

For the historical conditions, the Mediterranean Region, Hatay, Aegean Region, west of Central Anatolia, Yozgat and the localities between Gümüşhane and Amasya Provinces were determined to be suitable places, while the east and southeast areas of Anatolia and the coastline of the Black Sea appeared to be unsuitable places.

The distribution range of *A. ibrahimi* under the future conditions was mainly similar to the historical conditions, but it was more extensive than the historical climatic conditions. Also, Gallipoli and south of the mountains in Northeast Anatolia were determined to be suitable places.

Anatololacerta pelasgiana

The mean AUC values were calculated as 0.908±0.070, 0.902±0.071 and 0.921±0.072 for the LGM, historical and future bioclimatic conditions, respectively (Figure 5, Table 1). Under the LGM bioclimatic conditions, Hatay, Cilicia Region, Antalya Basin and the Aegean Region were seen to be suitable places.

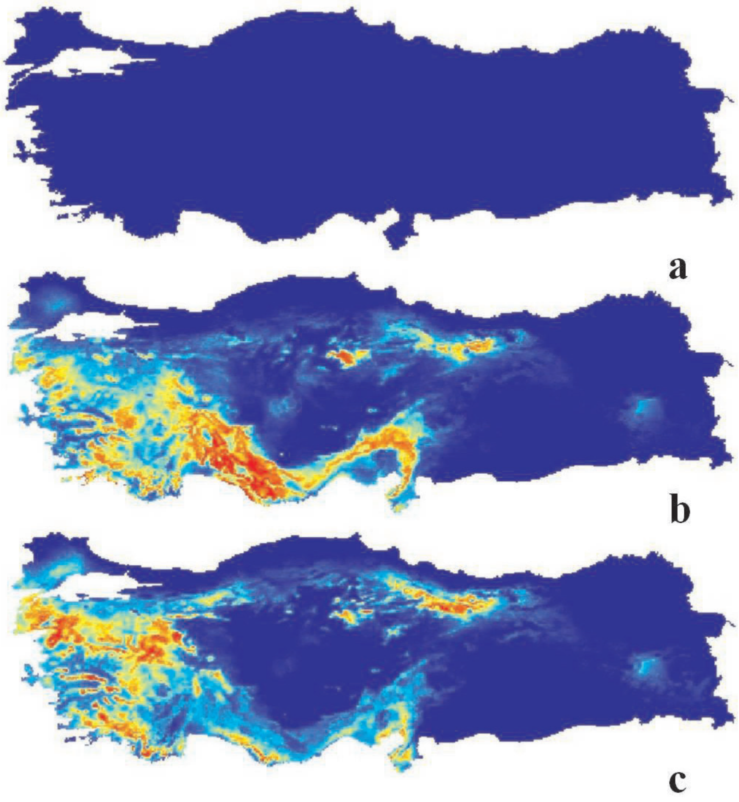

Fig. 4. Habitat suitability for *Anatololacerta ibrahimi* in Turkey. a) LGM; b) historical; and c) future bioclimatic conditions. Warm colours refer to highly suitable places on the map.

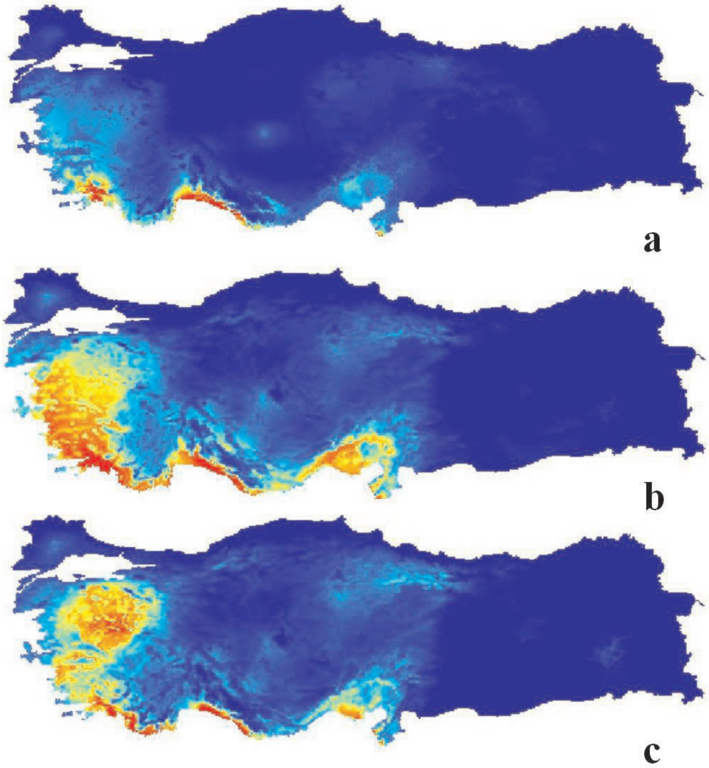

Fig. 5. Habitat suitability for *Anatololacerta pelasgiana* in Turkey. a) LGM; b) historical; and c) future bioclimatic conditions. Warm colours refer to highly suitable places on the map.

The distribution model in the historical conditions mainly fitted with that of the LGM, but the distribution was more suitable when compared with the LGM. It also widened towards the interior of Anatolia. East and Southeast Anatolia and the coastline of the Black Sea Region seem to be unsuitable places for *A. pelasgiana.*

The distribution range in the future mainly fitted with that of the LGM and historical bioclimatic conditions, but it was larger than in the LGM and smaller than in the historical conditions. While the Mediterranean and Aegean Regions and Hatay were suitable places for this species, the Cilicia Region, coastline of the Mediterranean Sea and south of the Marmara Sea were determined to be suitable places.

Discussion

In relation to speciation, Anatolia plays an important role and contains several refuges which have conserved species during ice ages and gave species the chance to migrate to suitable habitats during interglacial periods (GÜL *et al.* 2015). BELLATI *et al.* (2015) suggested that physical and climatic changes in the Pleistocene affected the distribution of the ancestral *Anatololacerta,* which allowed for an allopatric divergence of various lineages within Anatolia. Physical barriers could also have affected the divergence of species. While the Büyük Menderes River is considered to be a physical barrier between *A. anatolica* and *A. pelasgiana*, the Göksu River also isolated *A. danfordi* from the rest of *Anatololacerta* (BELLATI *et al.* 2015; KARAKASI *et al.* 2021). KARAKASI *et al.* (2021) suggested that there is no niche overlap for these five species belonging to *Anatololacerta* in the whole distribution region, except for one contact zone between *A. finikensis* and *A. ibrahimi*. In our study, possible distribution maps showed the niche overlaps for all species of *Anatololacerta* for both historical and future bioclimatic conditions, but physical barriers could restrict this possible niche overlapping.

The distribution of reptiles is influenced by anthropogenic factors including the human population size, trade, transportation and climatic changes (BICKFORD *et al*. 2010; SILVA-ROCHA *et al.* 2019). Global climatic changes also affect the distribution of many reptiles in different ways, leading to range expansion or habitat loss. One example of range expansion involves the Burmese python (*Python bivittatus*), which was introduced to North America by the pet trade. OSLAND *et al.* (2021) suggested that *P. bivittatus* could extend its range further north in response to winter warming. This assumption was tested not only in relation to invasive species but also to native species, and it has been predicted that some native species may expand or restrict their distribution range in the near future. SRINIVASULU *et al.* (2021) suggested that *Eryx whitakeri*, *Eutropis clivicola* and *Uropeltis phipsonii* may expand their ranges in Western Ghat with RCP 8.5, while the distribution range of *Kaestlea laterimaculata* may be restricted with RCP 4.5 in the same region. As a result of our study, we determined that while *A. danfordi*, *A. finikensis* and *A. ibrahimi* have the potential to expand their distribution range, there will be a potential narrowing in the distribution of *A. pelasgiana* and *A. anatolica.* However, the main question regarding this assumption is: how will they overcome the physical barriers? MARTINEZ-MEYER (2005) suggested that some barriers for one species may not be a barrier in the near future, and that ecological differences will make previously unsuitable areas suitable for certain species. This example provides an idea of how the physical barriers could be overcome. Our results also showed possible niche overlapping for members of the genus *Anatololacerta*. Thus, the interspecies competition that will emerge in the future will determine the species distribution, as well as the climatic suitability. LEGAULT *et al.* (2020) suggested that competition between species plays a large role during range expansions and that competition effects should be included in the models predicting future ranges.

As seen in our results, some species belonging to the genus *Anatololacerta* in Anatolia appear to have the potential to extend their range with the climatic changes occurring during the LGM and historical scenarios, as well as in the future RCP 4.5 scenarios. The range extension of the species determined by the models provides limited climatic information, but this assumption could be influenced by other factors such as species competition and physical barriers. Thus, our results suggest that the genus *Anatololacerta* should be monitored in the near future, with more locality records for niche overlapping and inter- or intraspecies competition.

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Author Contributions

Research concept and design; Collection and/or assembly of data; Data analysis and interpretation; Writing the article; Critical revision of the article; Final approval of article – E.B.

Conflict of Interest

The author declares no conflict of interest.

Supplementary Material

Supplementary Material to this article can be found online at:

http://www.isez.pan.krakow.pl/en/folia-biologica.html

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