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Ecological niche modeling of *Montivipera xanthina* (Gray, 1849) (Reptilia: Viperidae) under current and future scenarios in Anatolia and Southeastern Europe with additional new records from Türkiye

Emin Bozkurt[1*] and Arda Emre Kandil[2]

[1]Veterinary Department, Şabanözü Vocational School, Çankırı Karatekin University, 18100, Çankırı/Türkiye
[2]Ergotherapy Department, Faculty of Health Science, Çankırı Karatekin University, 18000, Çankırı/Türkiye
[*]Corresponding author: ebozkurt@karatekin.edu.tr

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Abstract

Global climate change affects the physical, morphological, and behavioral characteristics of reptiles. Sometimes reptiles may undergo spatial changes to cope with global climate change. Under the influence of global climate change, reptiles show many different responses, including habitat shifting, range expansion, habitat loss, or extinction. In this study, 117 locality records of *Montivipera xanthina* were used in conjunction with the program MaxEnt within the context of current (1981–2010) and five different future (2071–2100) climate change predictions (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-LL) in two shared socioeconomic pathways (ssp126 and ssp585). Further, habitat probability analysis was conducted for all predictions. The gain-loss analysis suggests that *M. xanthina* will lose 28.90% and 59.89% of the current distribution range under ssp126 and ssp 585 scenarios, respectively. The Bosphorus, Taurus Mountains in the Mediterranean region, Marmara region, and the Peloponnese were recovered as suitable areas of occupation in all future scenarios.

Key words: Habitat suitability, Ottoman viper, snake, probability

Introduction

Reptiles are affected by climate change because of their limited dispersal ability and many reptiles are localized endemics and live in restricted areas. For this reason, climate change can be an extinction threat for reptiles (Schneider and Root, 1998). Global climate change mainly affects nesting activities of some species and it has forced these reptiles to change the timing of nesting as well as nest location and depth. As a result, survival rates of embryos, phenotype of offspring, rate of parasitism and rate of predation can be affected by climate change (Du et al., 2023). Also, global climate change can affect some species with temperature-dependent sex-determination in three ways: increased temperatures will produce more females and increase resistance to climate change (Santidrián Tomillo and Spotila, 2020), females can change their reproduction strategy or nesting plasticity (Refsnider and Janzen, 2012), or if biased sex ratios reduce population viability, species with temperature-dependent sex-determination species may rapidly become extinct unless adaptive mechanisms, whether behavioral, physiological or molecular, exist to buffer these temperature-related effects (Lockley and Eizaguirre, 2021). However, the most accepted scenario is that climate change will result in extinction due to its rapidity (Hoffmann and Sgrò, 2011). Some species of reptiles can tolerate the impacts of climate change with altitudinal (Morena-Rueda et al., 2011) or spatial distribution changes (Osland et al., 2021).

Some can extend the distribution range after global climate change. One example of possible range extension is *Python bivittatus*, which in North America, where it is an invasive species, it is predicted to expand its distribution northward due to increasing winter temperatures (Osland et al., 2021).

The Ottoman Viper was first described in Xhantos ruins as *Daboia xanthina* by Gray in 1849. Boettger (1880) treated the specimens from Xhantos as *Vipera xanthina.* The genus *Montivipera* was separated from *Vipera* as a subgenus in terms of morphological, genetic, serological, and ecological differences by Nilson et al. (1999). The subgenus *Montivipera* was elevated the genus level by Joger (2005). Stümpel et al. (2016) divided *M. xanthina* into three lineages, an Aegean and Greek lineage and lineages in Lycia and the Taurus Mountains and they also defined the *bornmuelleri* complex by separating *M. bornmuelleri*, *M. albizona*, *M. bulgardaghica*, and *M. wagneri* from the *xanthina* complex. Cattaneo (2017) and Afsar et al. (2019) defined a new subspecies of *M. xanthina* in Greece as *M. xanthina occidentalis* and one in Türkiye as *M. xanthina varoli* in terms of canthals and dorsal scale rows, respectively, and these new subspecies agree with the lineages noted by Stümpel et al. (2016) to be different.

Montivipera xanthina has been the subject of earlier niche modeling attempts. Ahmadi et al. (2019) evaluated the years 2050 and 2070 in two different future scenarios (RCP 4.5 and RCP 8.5) under four different climatic models (GCM). While, Ahmadi et al. (2021) evaluated the niche modeling of ancestral lineages with six different bioclimatic data, Ahmadi et al. (2025) studied the mountain vipers with current phylogenetic niche modelling approaches and also performed probability analyses in the same study.

The study aims to investigate the possible distribution and habitat probability of *M. xanthina* in all distribution range in current (1981–2010) and future (2071–2100) under CMIP6's within 5 different climate change predictions (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-LL) in two shared socioeconomic pathways (ssp126 and ssp585). We also provide a new locality record for *M. xanthina* extralimital to the previously accepted range.

Material and Methods

The occurrence data for the species *M. xanthina* were obtained from 109 literature records and eight personal observations included a new locality record (Table 1). Some of the coordinates were directly taken from articles and others were georeferenced and checked by using Google Earth Pro version 7.3.2.

Bioclimatic variables were downloaded from CHELSA version 2.1 (https://chelsa-climate.org) with a spatial resolution of 30 arc-seconds (one km^2) (Karger et al., 2017). Pearson correlation analysis was calculated with an R-based NicheToolbox web application (Osorio-Olvera et al., 2020) and highly correlated variables were eliminated from the analysis ($r \geq |0.8|$). After correlation analysis, seven bioclimatic variables [Bio1 = Annual Mean Temperature; Bio2 = Mean Diurnal Range (mean of the monthly (max temp - min temp)); Bio3 = Isothermality (Bio2/Bio7) (×100); Bio8 = Mean Temperature of Wettest Quarter; Bio12 = Annual Precipitation; Bio14 = Precipitation of the Driest Month; Bio15 = Precipitation Seasonality] remained for next steps. The retained variables were used to predict the species niche under recent (1981–2010) and future (2071–2100) climate change predictions (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-LL) from the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al., 2016). When using climatic models, we used two shared socioeconomic pathways (ssp126 and ssp585) in which climate change is mediated through changes in greenhouse gas levels through social, economic, and environmental impacts. Ssps are based on estimates of greenhouse gas levels in the atmosphere and temperature increases at the surface. Accordingly, ssp126 is one of the optimistic scenarios, indicating low greenhouse gas emissions and 1.8 ºC warming in the global surface between 2081 and 2100. Ssp585 is the most pesimistic scenario, indicating very high greenhouse gas emissions and an estimated warming of 4.4 ºC between the same years (Intergovernmental Panel on Climate Change, 2021). All bioclimatic variables were clipped by ArcGIS 10.3.1.

We used the maximum entropy approach during the analysis. The R kuenm package, in conjunction with MaxEnt 3.4.4, was selected as the modeling tool for species distribution because it utilized presence and pseudo-absence data (Chambers, 2008; Phillips et al., 2009; Cobos et al., 2019). This approach allows for the estimation of a probability that ranges from 0 to 1 (Phillips et al., 2009). The distribution was assessed using a total of 10088 background points. A total of 341 candidate models were evaluated, each with different combinations of 11 regularization multiplier settings (ranging from 0.1 to 10), 31 class combinations of MaxEnt's five feature classes (hinge, threshold, product, quadratic, and linear), and a specific set of environmental variables. The models' performance was evaluated using statistical significance (Partial ROC), omission rates (OR), area under the curve (AUC) and Akaike information criterion corrected for small sample sizes (AICc). The studies by Hurvich and Tsai (1989), Anderson et al. (2003), Peterson et al. (2008), Rodríguez-Ruíz et al. (2020), and Kurnaz (2023) were referenced for this evaluation. The predicted distribution maps obtained from Maxent were imported into ArcGIS vers. 10.3.1 for a visualisation. We then used ArcGIS to predict the habitat probability of *M. xanthina* for mean 126 and 585 scenarios of gain-loss analysis.

Results

We identified a new population in Eldivan/Çankırı (40°29'0.30"N, 33°27'48.02"E). The distribution range of *M. xanthina* is extended nearly 186 km northeast of Polatlı (Eiselt and Baran, 1970) and nearly 76 km north of Kırıkkale (İlhan and Tosunoğlu, 2015) within this study (Fig. 1).

Table 1: Locality, coordinates and reference used in analyses.

Locality	Latitude	Longitude	Reference
Bodrum	37.0478	27.4689	Bird (1936)
İzmir	38.5043	27.1701	Bird (1936)
Adana	37.2460	34.8589	Bird (1936)
Karboğaz	37.1756	34.6425	Bird (1936)
Ankara	40.0365	33.1973	Bird (1936)
Efes	37.9460	27.3968	Bird (1936)
Spartakule	41.0665	28.7088	Bird (1936)
Kınık (Xanthos)	36.3629	29.2974	Eiselt and Baran (1970)
5 km south Kilitbahir	39.9978	26.5282	Eiselt and Baran (1970)
Geyikdere Village/Istanbul	40.6554	29.4593	Eiselt and Baran (1970)
Dereköy/Balıkesir	39.6127	27.7456	Eiselt and Baran (1970)
Polatlı/Ankara	39.1540	32.1261	Eiselt and Baran (1970)
Bornova/Izmir	38.4950	27.2743	Eiselt and Baran (1970)
Tavas/Denizli	37.6124	29.1106	Eiselt and Baran (1970)
Aksehir/Konya	38.3543	31.3765	Eiselt and Baran (1970)
Gölbasi-Demre/Antalya	36.2713	29.9285	Eiselt and Baran (1970)
Efes	37.9464	27.4024	Andren and Nilson (1975)
Çığlıkara	36.5147	29.7947	Andren and Nilson (1975)
Makri	40.8689	25.7414	Gardenfors (1980)
Loutros	40.9989	22.7136	Helmer and Scholte (1985)
Sikorrachi	40.9724	25.7339	Dimitropoulos et al. (1988)
İnegöl/Bursa	37.7806	27.8952	Teynie (1991)
Bozköy 20 km north of Germencik	39.0248	28.5503	Manteuffel (1993)
Akdağ-Hadim	36.9623	32.4680	Mulder (1995)
Selçuk	37.9565	27.3899	Mulder (1995)
Toka Plateau/Manavgat	36.8700	31.6393	Kumlutaş et al. (2004)
Belbaşı Plataeu/Gazipaşa	36.4775	32.4536	Kumlutaş et al. (2004)
Çamkuyu/Elmalı	36.5868	29.9921	Kumlutaş et al. (2004)
Avas	40.9328	25.9110	Petrov (2004)
Kazıklı-Bafa/Muğla	37.4207	27.5315	Kete et al. (2005)
Gümüldür	38.0764	27.0220	Arıkan et al. (2008)
Dereçine/Sultandağı/Afyon	38.4631	31.2440	Topyıldız (2008)
Göle-Ağı Mountain/Çanakkale	39.9681	26.9076	Topyıldız (2008)
Tekkedağ/Akşehir	38.3564	31.3784	Afsar and Tok (2011)
Kaş-Kekova	36.2002	29.8514	Kumlutaş et al. (2011)
Loutra	37.4426	24.4232	Cattaneo and Cattaneo (2013)
Pilea	40.9282	26.1130	Cattaneo and Cattaneo (2013)
Agnantia	40.8819	25.9735	Cattaneo and Cattaneo (2013)
Aetochori	41.0940	22.1631	Cattaneo and Cattaneo (2013)
Kavşit-Çine/Aydın	37.6588	28.1109	Özcan and Üzüm (2014)
Madran Village-Bozdoğan/Aydın	37.6713	28.2752	Özcan and Üzüm (2014)
Krovili	40.9484	25.5325	Cattaneo and Cattaneo (2014)
Askites	40.9306	25.5661	Cattaneo and Cattaneo (2014)
Dioni ve Strimi arası	40.9776	25.5463	Cattaneo and Cattaneo (2014)
Proskinites	40.9481	25.5010	Cattaneo and Cattaneo (2014)
Platanitis	40.8881	25.4896	Cattaneo and Cattaneo (2014)
Xilagani	40.9754	25.4364	Cattaneo and Cattaneo (2014)
Biga Peninsula	40.1221	26.5384	Tok and Çiçek (2014)
Biga Peninsula	40.2527	27.0429	Tok and Çiçek (2014)
Biga Peninsula	39.8570	26.8597	Tok and Çiçek (2014)
Biga Peninsula	39.7464	26.3981	Tok and Çiçek (2014)
Gelibolu Peninsula	40.3684	26.5769	Tok and Çiçek (2014)
Kırıkkale	39.8193	33.6833	İlhan and Tosunoğlu (2015)
Küçükdalyan Lake	36.6904	28.8035	Jablonski et al. (2015)
Kepez/Aydın	37.0043	30.6768	Stümpel et al. (2016)
Selçuk	37.9435	27.3914	Stümpel et al. (2016)
Olympos	37.9528	27.3935	Stümpel et al. (2016)
Tekiorva	36.5024	30.5103	Stümpel et al. (2016)
Loutros	40.9332	22.5356	Stümpel et al. (2016)
Kos	36.8923	27.2875	Stümpel et al. (2016)
Kohu Dağı	36.4920	29.7794	Stümpel et al. (2016)
Kumluca	36.3703	30.3870	Stümpel et al. (2016)

Table 1: (Continued).

Locality	Latitude	Longitude	Reference
Kratigos/Lesvos	39.0273	26.6054	Stümpel et al. (2016)
Efes	37.9310	27.3403	Stümpel et al. (2016)
Gediz Delta	38.6848	26.7690	Arslan et al. (2018)
Olympos	36.3941	30.4716	Mermer (2018)
Araplar Valley, Ezine/Çanakkale	39.8554	26.3535	Günay et al. (2018)
Enez/Edirne	40.7460	26.1432	Kurnaz et al. (2018)
Geyik Mountain	36.8641	32.0540	Afsar et al. (2019)
Geyik Mountain	36.8921	32.1412	Afsar et al. (2019)
5 km west of Cebir Melikgazi/Kayseri	38.5619	35.5611	Mebert et al. (2020)
9 km north of Develi, Develi/Kayseri	38.4672	35.5197	Mebert et al. (2020)
4.5 km north of Develi, Develi/Kayseri	38.4300	35.4811	Mebert et al. (2020)
3.5 km east of Subaşi, district Incesu/Kayseri	38.5442	35.2614	Mebert et al. (2020)
Between Dörtyol and Başdere, district Ürgüp/Nevşehir	38.5361	35.0908	Mebert et al. (2020)
Azatli Dam, Çiftlik/Niğde	38.1544	34.5378	Mebert et al. (2020)
2 km southwest Yenipinar, district Merkez/Aksaray	38.1594	34.2270	Mebert et al. (2020)
3 km northwest Kuşluca, district Erdemli/Mersin	36.8806	34.0603	Mebert et al. (2020)
3.5 km north of Akpinar, district Erdemli/Mersin	36.8433	34.0220	Mebert et al. (2020)
2 km southwest of Dervişli and 14 km straight north of Magara-Kirobasi, district Silifke/Mersin	36.8458	33.8008	Mebert et al. (2020)
8.5 km east of Özboynuinceli, district Erdemli/Mersin	36.9880	33.8358	Mebert et al. (2020)
Karadağ, district Merkez/Karaman	37.3728	33.1567	Mebert et al. (2020)
Karadağ, district Merkez/Karaman	37.3711	33.1442	Mebert et al. (2020)
Sariveliler/Karaman	36.7008	32.6158	Mebert et al. (2020)
Üçmuar Çeşmesi, Öteköy (Akdağ), district Alanya/Antalya	36.6403	32.2261	Mebert et al. (2020)
Ak Dağ, Hadim, district Hadim/Konya	36.9961	32.4319	Mebert et al. (2020)
Ak Dağ, Hadim, district Hadim/Konya	36.9878	32.4047	Mebert et al. (2020)
Hisarlik Plateau, district Hadim/Konya	36.9447	32.2600	Mebert et al. (2020)
Mount Barçin (Geyik Mountains), district Gündoğmuş/Antalya	36.8116	32.1491	Mebert et al. (2020)
Senir Yaylasi (Plateau), Gündoğmuş/Antalya	36.8675	32.0233	Mebert et al. (2020)
Geyik Mountains, Gelasandra Plateau, Gündoğmuş/Antalya	36.8581	32.0686	Mebert et al. (2020)
Kozağaci Mahallesi (Geyik Mountains), district Gündoğmuş/Antalya	36.8944	32.0502	Mebert et al. (2020)
3 km east of Cimiköy, district Akseki/Antalya	37.0258	31.8878	Mebert et al. (2020)
Yazir Mahallesi, district Selçuklu/Konya	37.9731	32.4553	Mebert et al. (2020)
Mevlütlü, district Tuzlukçu/Konya	38.5611	31.6297	Mebert et al. (2020)
Honaz Mountain/Denizli	37.6931	29.2394	Gidiş and Başkale (2020)
Isparta	37.7175	30.4902	Ahmadi et al. (2021)
Tekirova	36.5275	30.5063	Ahmadi et al. (2021)
Samothraki	40.4477	25.5918	Cattaneo (2022)
Lesvos	39.2534	26.3027	Cattaneo (2022)
Chios	38.3770	26.0909	Cattaneo (2022)
Samos	37.7332	26.9542	Cattaneo (2022)
Patmos	37.3130	26.5469	Cattaneo (2022)
Lipsi	37.2986	26.7463	Cattaneo (2022)
Leros	37.1431	26.8424	Cattaneo (2022)
Kalmynos	36.9606	26.9869	Cattaneo (2022)
Symi	36.5793	27.8432	Cattaneo (2022)
Evros	41.2192	26.1304	Cattaneo (2022)
Hisarönü/Köyceğiz	36.5637	29.1222	Bozkurt et al. (2022)
Oluklar Plateau/Antalya	36.4770	29.6499	Personal observations of authors
Patara	36.2712	29.3174	Personal observations of authors
Kohu Mountain	36.4871	29.9353	Personal observations of authors
Göcek Peninsula	36.7612	29.0145	Personal observations of authors
Eldivan/Çankırı	40.4834	33.4633	Personal observations of authors (New locality record)
Ekincik	36.8294	28.5470	Personal observations of authors
Çayırhan/Ankara	40.1391	31.4719	Personal observations of authors
Akçatekir	37.3601	34.6931	Personal observations of authors

Figure 1: General view of *M. xanthina* from Eldivan/Çankırı, Türkiye (Photographed by Arda E. Kandil).

The distribution of *M. xanthina* is mostly influenced by two bioclimatic variables: precipitation seasonality (Bio 15) (50.1%), and mean diurnal air temperature range (Bio 2) (16.2%). Other factors had a contribution that was lower than the tenth percentile (Table 2).

The optimal model for determining the possible distribution of this species was chosen based on the lowest AICc scores and validated using the average AUC scores. Out of the 341 candidate models that were analyzed, 339 showed statistical significance according to the pROC test ($P < 0.05$). The regions identified as suitable habitats for *M. xanthina* had a significant area under the curve (AUC) of 0.811±0.022. However, only one of them satisfied the AICc condition of being less than or equal to 2 (ΔAICc = 0.321). This model is a combination of quadratic and product features, and it has a mean area under the curve ratio of 1.328. The Mediterranean coast of Türkiye, Aegean parts of Türkiye, Boshoporus, the south of Thrace, the island of Crete, and Peloponnese were seen as suitable places for current bioclimatic conditions (Fig. 2). Under the current conditions, 26.32% of the studied area was determined as unsuitable while 9.78% of the studied area was found as highly suitable for *M. xanthina* (Table 3 and Fig. 3).

For future predictions, IPSL-CM6A-LR with the ssp 126 was determined as a highly optimistic scenario. MaxEnt predicts that 9.41% of the studied area is a highly suitable habitat, while 28.27% of all areas were determined as unsuitable habitat. The pessimistic scenario is GFDL-ESM4 with 35.48% and 7.71%, unsuitable and highly suitable habitats, respectively (Fig. 4).

Table 2: The environmental layers utilized in the species distribution modeling of *Montivipera xanthina* were assessed for their permutation importance and percentage contribution.

Bioclimatic variables	Percent contribution	Permutation importance
Bio1 (Annual mean temperature)	2.4	1.4
Bio2 (Mean diurnal range)	16.2	29.8
Bio3 (Isothermality)	7.1	6.3
Bio8 (Mean temperature of wettest quarter)	6.6	7.4
Bio12 (Annual precipitation)	8.1	7.0
Bio14 (Precipitation of the driest month)	9.3	10.7
Bio15 (Precipitation seasonality)	50.1	37.4

Table 3: Predicted the suitability of *Montivipera xanthina* as a result of probability analysis.

Models	Ssp	Unsuitable (%)	Low (%)	Moderate (%)	High (%)
Current		26.32	40.94	22.95	9.78
GFDL-ESM4	126	35.48	37.95	18.86	7.71
	585	26.74	49.55	18.07	5.63
IPSL-CM6A-LR	126	28.27	41.43	20.90	9.41
	585	37.48	40.08	18.13	4.31
MPI-ESM1-2-HR	126	33.78	37.52	19.59	9.11
	585	72.28	18.65	6.52	2.55
MRI-ESM2-0	126	28.14	43.44	20.57	7.85
	585	31.32	48.56	15.95	4.18
UKESM1-0-LL	126	27.92	43.50	21.19	7.39
	585	47.70	34.39	14.89	3.02
Mean	126	28.50	43.34	20.06	8.10
	585	35.34	45.26	15.71	3.69

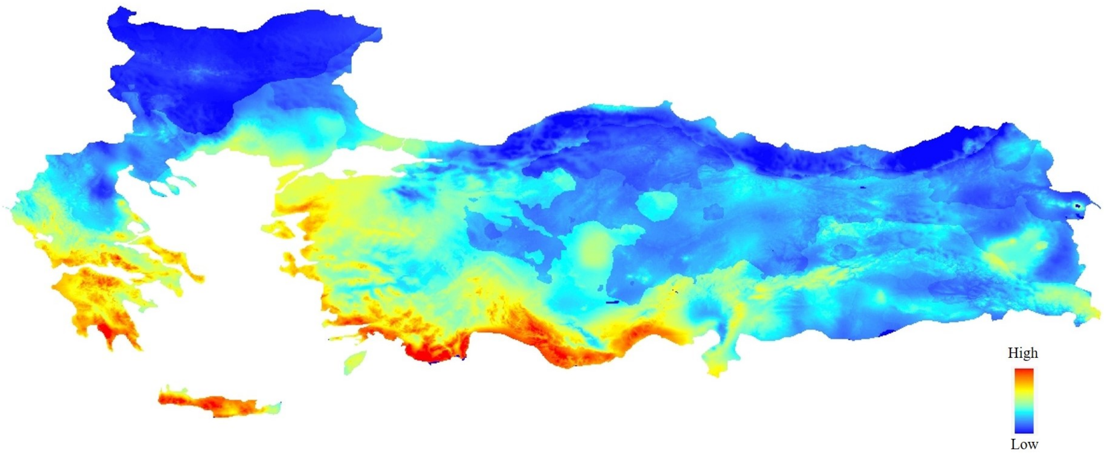

Figure 2: Current habitat suitability of *Montivipera xanthina* (warmer colors refer to a high suitability level).

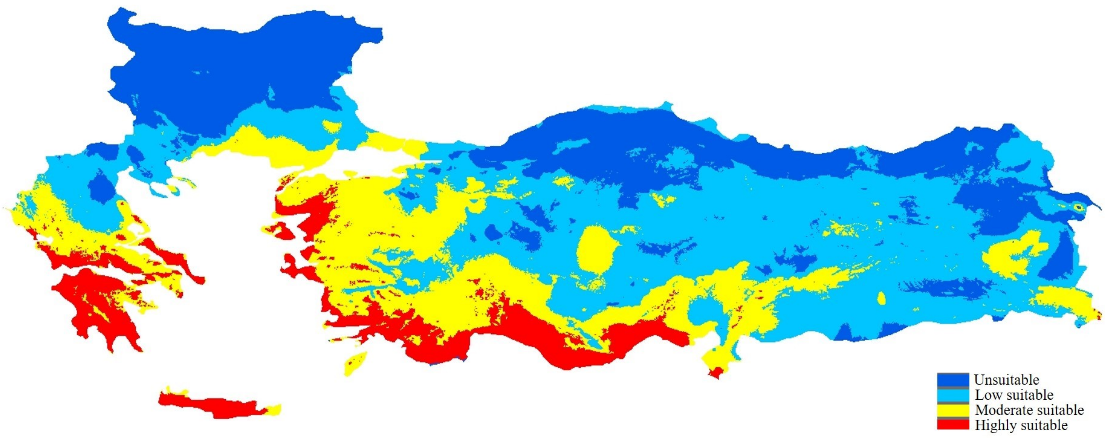

Figure 3: Estimation of suitable habitat predicted of *Montivipera xanthina* under current bioclimatic conditions.

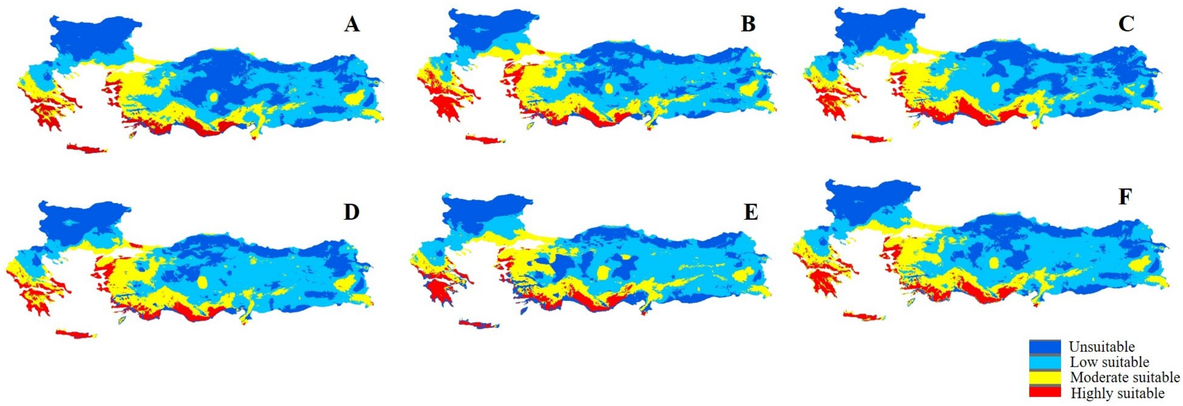

Figure 4: Habitat probability distribution of *Montivipera xanthina* in terms of ssp 126 models. (A) GFDL-ESM4, (B) IPSL-CM6A-LR, (C) MPI-ESM1-2-HR, (D) MRI-ESM2-0, (E) UKESM1-0-LL (ssp 126), (F) Mean of 5 models (warmer colors refer to high suitability level).

For all models of ssp 126, the Mediterranean coast of Türkiye, Aegean parts of Türkiye, the south of Thrace, Marmara Sea region, Bosphorus, island of Crete, Peloponnese, and southern part of continental Greece were seen as suitable places for these conditions (Fig. 5). Under these conditions, *M. xanthina* appears to have reduced its distribution range.

According to future predictions of ssp 585, MPI-ESM1-2-HR was determined as the most pessimistic scenario. Analysis shows that 72.28% of the total studied area comprises unsuitable habitats, while 2.53% of all areas were determined as highly suitable habitats. The most optimistic scenario of ssp 585 is GFDL-ESM4. It is observed that 26.74% of all studied areas seem as unsuitable while 5.63% of them were found to be highly suitable habitats for *M. xanthina* (Fig. 6). The Mediterranean coastline of Türkiye, Bosphorus, Thrace, Crete, and southern Peloponnese were seen as suitable places for these conditions (Fig. 7). Under these conditions, the distribution range of *M. xanthina* is narrower than current conditions and all future scenarios.

According to analysis for ssp 126 and ssp 585 scenarios, the distribution range of *M. xanthina* would be narrower than current climatic conditions. As a result of gain-loss analysis for ssp 126, *M. xanthina* would increase the distribution range by 5.59%, while it would decrease by 34.49% of its historical range. In total, the distribution range of *M. xanthina* would be narrower by 28.90%. For the ssp 585 model, the situation is more dramatic. *M. xanthina* would lose 59.89% of its distribution range (Fig. 8). This analysis also showed that *M. xanthina* would be occured in the mountainous areas and northern parts of its current range.

The new locality record (Eldivan, Çankırı) is located in areas shown as low suitability areas in current and future scenarios. Also, when looking at the gain-loss analyses, it appears as lost areas in ssp 126 and ssp 585 scenarios.

Discussion

Stümpel et al. (2016) suggested that climatic oscillations and mountain systems constituted microhabitats and that these microhabitats acted as refugia and affected the evolution of *Montivipera*. After glacial periods, *Montivipera* colonized coastal regions and today, *M. xanthina* is distributed from semi-elevated upland to low-elevation plains in Türkiye and Greece (Ahmadi et al., 2021). Yousefi et al. (2015) studied the *Montivipera raddei* complex and suggested that global climate change will restrict the distribution of populations to allopatric mountaintops in the future. As a result of our analysis with current bioclimatic data, the coastal parts of the Mediterranean, Aegean, Marmara, Crete, and Peloponnesus were found to be the most suitable areas for the distribution of *M. xanthina*, and this situation supports the results of Ahmadi et al. (2021). In addition, in future projections, coastal areas and plains are seen as suitable areas for *M. xanthina*, instead of mountainous regions, contrary to what Stümpel et al. (2016) and Yousefi et al. (2015) suggested.

Although Crete, the Peloponnese, the south of Greece, and the east of the Mediterranean coast of Türkiye were found to be suitable areas in some models according to the analysis, they do not match the current distribution of the *M. xanthina*. Sometimes, due to human-induced effects, species can move to different areas in their natural distribution area, settle there, and reproduce in these areas. Climatic suitability is an important factor in this situation. Historical records show that *Hemidactylus turcicus* was a species native to the Mediterranean, but has spread to America today due to human influence (Carranza and Arnold, 2006; Martinez-Hernandez et al., 2017). According to niche model analyses, it is predicted to expand its distribution to Argentina, South Africa, South Australia, and the southern coasts of the Mediterranean (Weterings and Vetter, 2018).

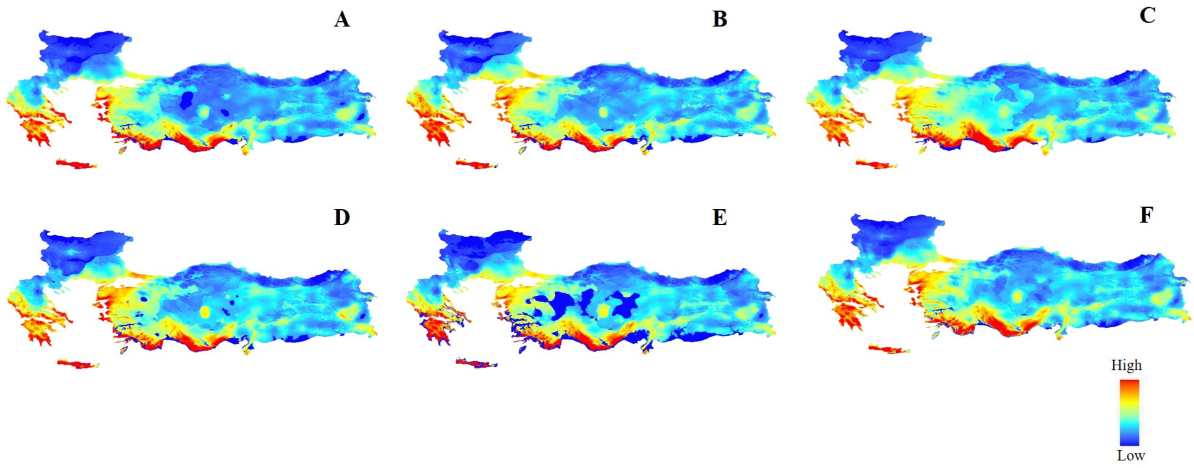

Figure 5: Future habitat suitability of *Montivipera xanthina* in terms of ssp 126 models. (A) GFDL-ESM4, (B) IPSL-CM6A-LR, (C) MPI-ESM1-2-HR, (D) MRI-ESM2-0, (E) UKESM1-0-LL (ssp 126), (F) Mean of 5 models (warmer colors refer to high suitability level).

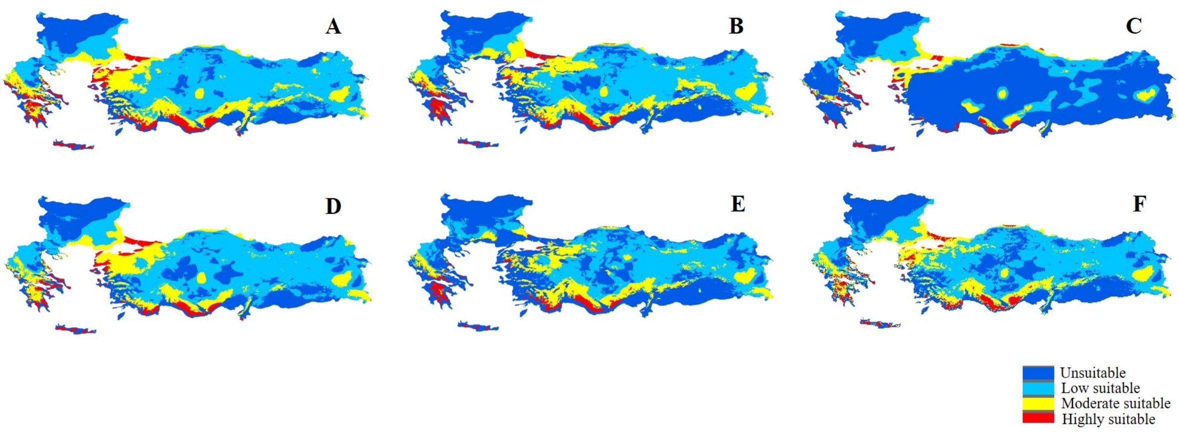

Figure 6: Habitat probability distribution of *Montivipera xanthina* in terms of ssp 585 models. (A) GFDL-ESM4, (B) IPSL-CM6A-LR, (C) MPI-ESM1-2-HR, (D) MRI-ESM2-0, (E) UKESM1-0-LL (ssp 126), (F) Mean of 5 models (warmer colors refer to high suitability level).

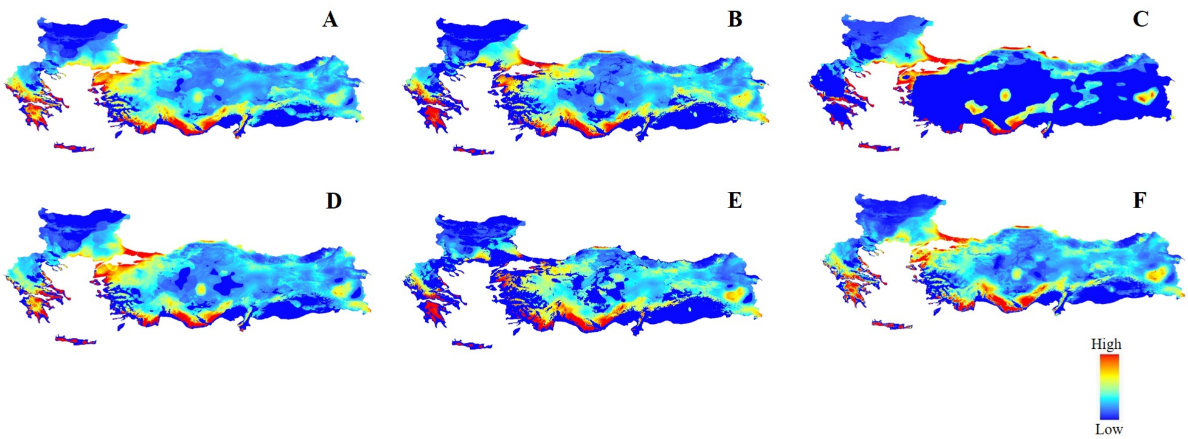

Figure 7: Future habitat suitability (2071–2100) of *Montivipera xanthina* in terms of ssp 585 models. (A) GFDL-ESM4, (B) IPSL-CM6A-LR, (C) MPI-ESM1-2-HR, (D) MRI-ESM2-0, (E) UKESM1-0-LL (ssp 126), (F) Mean of 5 models (warmer colors refer to high suitability level).

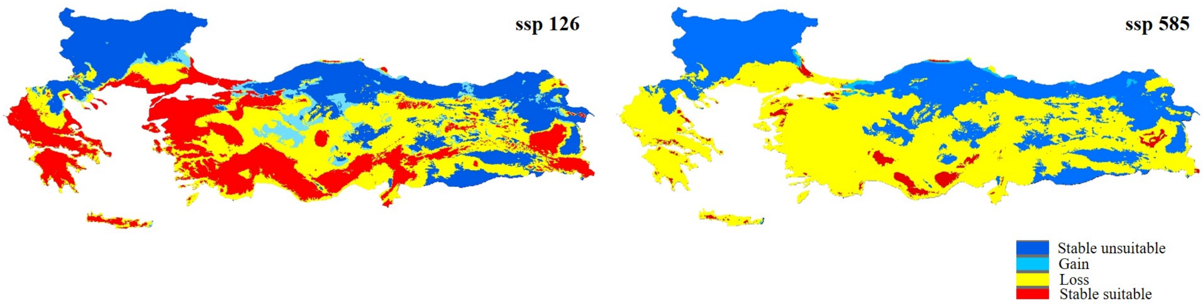

Figure 8: Habitat gain and loss results of *Montivipera xanthina.*

According to Martinez-Meyer (2005), after climatic changes, some geographical structures may cease to be barriers in the future. Considering all these data, we can expect the most probable expansion of *M. xanthina* to be to the eastern part of the Mediterranean coast of Türkiye. However, it should be noted that in addition to ecological niches, many biotic and abiotic factors also affect species distribution, and this does not mean that *M. xanthina* will settle in these suitable areas in the future.

Biber et al. (2023) suggested that reptile species richness will decrease globally under future climatic scenarios, while increasing in Palaearctic regions, including Türkiye and Greece. Gül et al. (2023) also stated that six *Lacerta* species that live in Türkiye will expand their ranges in two different future projections. Vaissi et al. (2023) studied the 12 *Ablepharus* species and found that the distribution range of nine of them will decrease while the distribution range of three of them will increase in different future scenarios. Contrary to these studies, all models used in this study show that the distribution of *M. xanthina* will narrow.

Ahmadi et al. (2019) revealed that the distribution range of *M. xanthina* will decrease in the 2050–2070 projection by nearly 63.8% and the area under highest threat in the future will be in Mediterranean mountains. In our study, a reduction of the distribution range was also found but a mountain zone of the Mediterranean is recovered as a highly suitable area in 2071–2100 projections under different models.

Ahmadi et al. (2021) reported that temperature seasonality (Bio4), temperature of the warmest month (Bio5), precipitation seasonality (Bio15), and precipitation of the driest month (Bio17) were the most important climatic variables for almost all *Montivipera* species. According to Kurnaz (2023), the most important bioclimatic variables for *M. albizona* and *M. bulgardaghica* are annual temperature range (Bio7) and mean temperature of the coldest quarter (Bio11). Ahmadi et al. (2025) stated that under current climatic data, wettest month (Bio13) is the most important bioclimatic data for *M. xanthina* living in the Aegean and Lycian regions and temperature seasonality (Bio4) is the most important bioclimatic data for those living in Greece. However, in our study, precipitation seasonality (Bio15) for *M. xanthina* showed the highest level of importance while Bio4, Bio5, Bio7, Bio11, and Bio17 were found to correlate with other parameters and all of them were excluded from the analysis. Cattaneo (2022) stated that *M. xanthina* lives in humid areas of the mountains and is also found in the plains of northeastern Greece, but this area also receives plenty of rainfall. Therefore, precipitation may have been important in determining the distribution of the species. The geographic distribution of suitable habitats of *M. xanthina* in our study also showed similarity with Ahmadi et al. (2021). As a result of our study, the situation seems quite dramatic for *M. xanthina* according to the ssp585 model. One of the aims of this study is to create a resource for the conservation of *M. xanthina*. According to Schwartz (2012), niche modeling creates an opportunity for conservation efforts by identifying new areas rather than assuming that existing areas will disappear. In addition, four types of decisions are made during conservation work and these are policy, habitat protection, habitat management, and species management. In this respect, we think that the current areas in the species' distribution and the areas that appear suitable in the future in niche modeling should all be protected. In addition to habitat-based protection, we also recommend that species-based management be taken for existing populations in order for the species to persist in the future.

Many biotic and abiotic factors affect the life of animals. Snakes are top of the list of misunderstood, mistreated, feared, or killed animals (Pandey et al., 2016). According to a study of students conducted in America, it was determined that the probability of people killing poisonous snakes they encounter was 36%, the probability of killing non-poisonous snakes was 9%, and the probability of killing any snake was 21% (Vaughn et al., 2022). Urbanization also affects snake life in different ways; fragmentation or degradation of natural systems, creation of new environmental conditions, and introduction of invasive or exotic species, pathogens, and toxic contaminants (Lettoof et al., 2023). Climate change can have nultiple affects on snakes; range extension (Pyron et al., 2008), habitat loss (Ahmadi et al., 2019), and risk of extinction (Böhm et al., 2016).

Snakes can cope with climatic conditions by adapting to new conditions, shifting, widening, or narrowing ranges, and isolating them into unaffected areas or climatic refuges (Lourenço-de-Moraes et al., 2019). However, increasing human influence may not allow species to achieve this climatic adaptation.

Conclusion

Our study predicts that the distribution range of *M. xanthina* will decrease in the near future. Since we cannot reduce the increasing human impact under current conditions, we must try to preserve *M. xanthina* in ecologically suitable areas. Therefore, this study reveals the ecological areas necessary for the conservation of *M. xanthina*.

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Author contributions

E. B. and A. E. K. designged the study and conducted field study. E. B. analyzed the niche models and wrote the manuscript.

Conflicts of interest

The authors declare that there are no conflicting issues related to this research article.

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