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Abstract

Despite their rich diversity, reptiles have been the subject of fewer ecological investigations than other vertebrate groups. Understanding the spatial distribution of reptiles is crucial due to their specific habitat needs and limited locomotion ability. Morgan's black cobra (*Walterinnesia morgani*) is a venomous and secretive snake species that has received little attention in the Iranian scientific literature till now. The aim of the present study was to reveal the existing distribution pattern of the cobra and to speculate on how climatic changes might affect it. Maximum entropy modeling was used to examine a dataset consisting of 17 occurrence records gleaned from the literature and field observations. The niche of the species was predicted using current and future climate change forecasts and bioclimatic and topographical characteristics. The models predicted a future reduction in the wide distribution region of *W. morgani* in southern and western Iran. It was discovered that climatic factors like temperature range, precipitation dynamics, and river proximity all played a key role in shaping the pattern of dispersion. The predicted suitable areas for *W. morgani* were dependent on water sources; however, future scenarios showed a decline in suitable habitats.

This study underscores the importance of conservation efforts in light of the potential implications of climate change on this species. To further understand the range shifts and adaptation strategies of the species, further study of its ecology and dispersal dynamics is required.

Keyword: Ecological niche, Morgan's black cobra, MaxEnt, precipitation, topography

Introduction

Reptiles, although they account for one-third of global terrestrial vertebrate diversity, have lagged behind other groups, such as birds and mammals, in terms of ecological studies (Biber et al. 2023). Due to the fact that reptiles are typically characterized by specific habitat needs and limited locomotion ability (Guedes et al. 2018), understanding their spatial distribution is crucial. In this regard, revealing species distribution patterns improves our knowledge of ecological diversity regarding the relationship between landscape and species. Climatic oscillations, like topographic and vegetation cover patterns, have contributed to the species' distribution in different biomes.

Despite reptile species being widely distributed throughout the world, they are at risk of extinction due to habitat loss and degradation, pollutions, invasive species, diseases, and climate changes (Gibbons et al. 2000). Anthropogenic impacts—not only habitat use but also misbeliefs about their poisonous status—have disproportionately threatened snake species within the class Reptilia (Saha et al. 2018). Therefore, evaluating the conservation status of these quite secretive organisms and determining their distribution patterns are important.

The herpetofauna of Iran comprises 81 species of snakes belonging to 34 genera and 7 Families (Rajabizadeh 2018). Family Elapidae, including Elapinae (3 genera, 3 species) and Hydrophiinae (1 genus, 10 species), is more diverse than Viperidae, including Crotalinae (1 genus, 1 species) and Viperinae (7 genera, 10 species) (Safaei-Mahroo et al. 2015;

Rajabizadeh 2018). Despite the increasing trend to discern the distribution pattern of herpetofauna elements in Iran (Hosseinian Yousefkhani 2019; Vaissi 2021a, 2021b, 2022), snake species are less studied in that country (Hosseinzadeh et al. 2017; Moradi et al. 2021).

The genus *Walterinnesia* Lataste, 1887 has two species known commonly as desert black snakes or black desert cobras including the type species *Walterinnesia aegyptia* Lataste, 1887 and *Walterinnesia morgani* (Mocquard, 1905) (Fig. 1). Both species occur only in the Middle East, as the type locality of *W. morgani* is Khuzestan Province in the southwest of Iran (Uetz et al. 2023). Populations of the species in Iran have been considered as *W. aegyptia* by Farzanpay (1989); Latifi (1985, 1991, 2000); and Leviton et al. (1992). Nilson and Rastegar-Pouyani (2007), based on the lower scale row counts around the neck and having a banded juvenile pattern (Fig. 2), recognized the eastern populations of the genus (from Türkiye and Saudi Arabia to Iran) as *W. morgani*; however, Rajabizadeh (2018) considered the Iranian populations of the genus as *Walterinnesia aegyptia morgani*.

Black desert cobras are nocturnal, so they are most active when it is cooler at night (Uğurtaş et al. 2001). During the hottest parts of the day, they seek refuge in burrows or beneath rocks. The seasonal activity of desert cobras may be influenced by local climate conditions (Baran et al. 2006). In some regions, for instance, they may be less active during the hottest period of summer and more active during the cooler months. Nonetheless, they are capable of being active even in extreme temperatures and are acclimated to harsh desert environments.

In spite of the known distribution of Morgan's black cobra *W. morgani* in the Central and Southern Zagros Mountains, and its medical importance (Abid et al. 2020), the national literature on the species is scarce. The main reason for this is probably the difficulty of studying this mysterious and nocturnally active poisonous snake. Therefore, the aim of this study was to reveal the current pattern and speculate on the effects of climate oscillations on the distribution pattern of the black desert cobra in Iran.

Materials and Methods

This study was conducted within the borders of the Islamic Republic of Iran (44.04–63.31°E and 25.08–39.77°N). A total of 17 occurrence records of *W. morgani* were obtained from the literature and our field observations (Farzanpay 1989; Latifi 2000; Nilson and Rastegar-Pouyani 2007; Fathinia et al. 2010; Gholamifard et al. 2012; Gholamifard and Rastegar Pouyani 2012) (Table 1). In cases where the locality information was not provided in any GPS format, an online geographic system application (i.e., Google Earth Pro) was used to ascertain the most precise location possible. All records were georeferenced using the WGS84 coordinate system and checked with (QGIS Development Team 2023). To reduce the effects of spatial autocorrelation (Boria et al. 2014) using the R package *spThin*, we utilized occurrence data that were separated by more than 2 km (Aiello-Lammens et al. 2015). One of the main issues with ENM is that it may lead to model overfitting if a large number of predictor variables are used in conjunction with a small sample size (Fielding and Bell 1997). Therefore, the Akaike Information Criterion corrected for small sample sizes (AICc) was applied to the distribution pattern (Hurvich and Tsai 1989).

Bioclimatic variables were downloaded from the CHELSA database (https://chelsa-climate.org/) at a spatial resolution of 30 arc-second raster grids (Karger et al. 2017; Brun et al. 2022). Additionally, two topographic variables were obtained from the study of (Gavashelishvili et al. 2018) (Supplementary File 1). Each layer was clipped for the study area in QGIS. Pearson correlations between variables were calculated in R v4.3 (R. Core Team 2023) and highly correlated variables were eliminated ($r \geq |0.8|$). All used variables were employed to predict the species niche under recent (1970–2000) and future (2081–2100) climate change projections (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-LL) with the lowest and the highest limits of the shared socioeconomic pathways (SSPs) from the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al. 2016) (Supplementary File 2).

Maximum entropy modeling was utilized since it is a robust method that can be applied to presence and pseudo-absence data. Based on presence and pseudo-absence data, this algorithm can predict the presence of a species with a probability between 0 and 1 (Phillips et al. 2009). A total of 2000 background points for *W. morgani* were sampled at random throughout the survey area. The potential habitat suitability was modeled by implementing MaxEnt 3.4.1 in R using the *kuenm* package (Phillips et al. 2017; Cobos et al. 2019). To create the models for this cobra species, 80% of the occurrence data was used for generating the candidate models, and the remaining 20% for independent presence as test data.

In order to optimize the model complexity for the cobra species, 31 combinations of MaxEnt's 5 feature classes [hinge (h), threshold (t), product (p), quadratic (q), and linear (l)] along with 17 regulation multiplier values (0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 2, 3, 4, 5, 6, 8, 10) were evaluated. This combination of variety enabled us to reach the best-fitting model that best represents our data by generating diverse candidate models (Muscarella et al. 2014; Cobos et al. 2019). Following that, the Akaike Information Criterion corrected for small sample sizes (AICc) (with the lowest values) as well as the AUC values (with the highest values) were both used to determine the best models (Hurvich and Tsai 1989). Significance tests were performed using partial ROC (Peterson et al. 2008) and predictive power with a 5% omission rate (Anderson et al. 2003). Lastly, all model inputs were transformed into binary predictions by using the minimum training presence as the threshold to distinguish suitable areas from unsuitable ones (Pearson et al. 2007; Şahin et al. 2022).

Results

The areas predicted to be suitable for *W. morgani* had a high AUC of 0.955±0.014 and the lowest AICc and delta AICc values were 0.169, 0, respectively, for the recent historical and future bioclimatic projections (2081–2100) under SSP126 and SSP585 scenarios (Figs 3, 4A–J; Table 2). Six climatic and two topographic variables were employed according to the Pearson correlation coefficient: mean diurnal air temperature range (Bio_2 hereafter), annual range of air temperature (Bio_7 hereafter), daily mean air temperatures of the driest quarter (Bio_9 hereafter), precipitation amount of the driest month (Bio_14 hereafter), precipitation seasonality (Bio_15 hereafter), mean monthly precipitation amount of the driest quarter (Bio_17 hereafter), distance to river (d_river hereafter), elevation (elev hereafter). The contributions of the variables are given in Table 3.

The fact that the AUC data were very close to 1 showed that the distribution area revealed by the locality data obtained from the distribution area of the desert cobra displayed a much better performance than a random prediction.

According to the analysis outputs, the distribution area of *W. morgani* covers a water source-dependent pattern in western Iran. Additionally, as can be seen in future climatic conditions, the distribution range would be narrower than under recent historical conditions. In the future, it is expected that the possible distribution of *W. morgani* will contract in southwestern Iran.

Discussion

Walterinnesia morgani, commonly known as Morgan's black cobra or black desert cobra, is a venomous snake species that inhabits the Arabian Peninsula (Kuwait and Saudi Arabia), the extreme south of Türkiye, Syria, and the majority of Iraq, as well as western and southern Iran (Ilam, Kermanshah, Khuzestan, Bushehr, Fars, and Hormozgan Provinces) (Gasperetti 1988; Joger 1984; Latifi 2000; Uğurtaş et al. 2001; Sindaco et al. 2006; Safaei-Mahroo et al.

2015). In a specific concept, the Zagros Mountains display a wide biodiversity pattern, as well as the Central Iranian Plateau and the northern Persian Gulf, in one of the well-known biodiversity hotspots (Irano-Anatolian Biodiversity Hotspot) in the Palearctic Realm (Gholamifard 2011; Mittermeier et al. 2011). *W. morgani* is one of the representative charismatic species of this region, where the shiny black color of this snake attracts attention and increases the excitement caused by seeing a poisonous and mysterious snake; this is very important from the aspect of the conservation status of the species, as most of the sightings of this species lead to its death. Therefore, the results of this study present an insight for understanding the range dynamics pattern of *W. morgani* in scale to Iran.

Numerous biotic and abiotic factors have significant impacts on the distribution of the species (Pearson et al. 2007). In order to comprehend the responses of *W. morgani* to the climatic oscillations during recent history and future possible scenarios, we employed ENM as a useful analytical biology instrument to assess the range of the species. Because climate changes affect all aspects of biodiversity, from organisms (organismal diversity) to biomes (ecological diversity) (Gaston and Spicer 2004), and pose a significant threat to the integrity of ecosystems (Bellard et al. 2012). Additionally, it is most likely speculated that vertebrate species will face serious adaptation problems related to alterations in their climatic niches in the near future (Quintero and Wiens 2013). It should be noted that the distribution of reptiles is significantly affected by direct and/or indirect anthropogenic activities, such as human population size and human-driven climatic changes (Bickford et al. 2010).

Based on these results, most of the suitable predicted areas were slightly wider than the present distribution of *W. morgani*. This might be the possible effect of “d_river” as one of the highest contributors to shape the distribution pattern via the water requirement of the species. Additionally, daily and annual temperature cycles have also contributed to the distribution pattern as well as the seasonal factors, especially the driest seasonal precipitation dynamics. This overall bioclimatic and topographic pattern is observed in many reptile species in the study area and its close geography (Kurnaz and Eroğlu 2021; Şahin et al. 2022a, 2022b; Vaissi 2022).

On the other hand, our results show that there is a decrease in suitable habitats for *W. morgani*, but the level of the decreasing trend varies depending on the SSP levels and different future scenario sets. This trend is compatible with many ecological niche modeling studies that were applied to reptiles in the study area and nearby regions (Bozkurt 2022). Additionally, this contraction pattern was also speculated on for many lizard species' future distribution trends (Vaissi 2022). Nonetheless, the genus Lacerta Linnaeus and two leopard geckos present an opposite trend in the Anatolian Peninsula and Iran, respectively (Hosseinian Yousefkhani and Nabizadeh 2022; Gül et al. 2023).

When compared to other large vertebrates groups, the ability of reptiles to migrate is quite restricted (Hickling et al. 2006). Moreover, our knowledge about the ecology and dispersal dynamics of *W. morgani* has received little or no attention. Based on Figure 3 and 4, the current research assumed an infinite capacity for dispersal across species and made predictions about its range changes through 2100. Despite contractions and expansions, the distribution range of the species in each ssp126 looks to remain mostly unchanged (Fig. 4A, C, E, G, I); however, in ssp585, the species will be contracted in southwestern Iran (Fig. 4B, D, F, H, J). Additional factors, such as geographic barriers, may influence the migration rate of a species (Morena-Rueda et al. 2012). In our case, distance to the river and elevation parameters, as topographic variables, have significant contributions to the species distribution. Even though the Zagros Mountains can be assessed as a remarkable geographic barrier, the main limitation factor is the "distance to the rivers" for *W. morgani*. Because it seems that the cobra tends not to be so distinct from water resources.

On the other hand, the model algorithm that was used in this study did not take into account some parameters, such as parasitism, disease, habitat loss, and fragmentation that might affect species realistic distribution (Todd et al. 2010). In the meantime, a recent study that focused on the snake bite risk in Iran showed that the northern and western parts of Iran would have more risk than the rest of the country (Yousefi et al. 2023). However, our results pointed out that southwestern Iran could be a potential suitable region for Morgan's black cobra. No common species distribution model was reported for the distribution of *W. morgani*, neither country-based nor across-range, by including up-to-date topographic variables. Thus, our results suggest that *W. morgani* is recommended to be monitored in the near future, with more occurrence records for better understanding of its distribution and increasing awareness of human–cobra conflict due to many aspects of anthropogenic activities. To sum up, it is desirable to predict the distribution of this species in Iran from the aspect of medical treatment of possible bites of the species and to prepare its antivenom.

Author contributions

A. Gholamifard and M.K. Şahin conceived the study. A. Gholamifard collected the field data and documentation. M.K. Şahin carried out the sampling design, statistical analysis and performed modeling. A. Gholamifard and M.K. Şahin contributed equally for writing the manuscript.

Conflict of interest

The authors have no conflict of interest.

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Tables and Figure Captions

Table 1. Species occurrence records of *W. morgani* in Iran from literature and our field trips.

Species	**Latitude**	**Longitude**	**Locality**	**References**
Walterinnesia morgani	32.07° N	48.87° E	Sushtar, Khuzestan Province	GBIF
Walterinnesia morgani	34.45817° N	45.85539° E	Sarpol-e Zahab, Kermanshah Province	Farzanpay (1989); Gholamifard and Rastegar-Pouyani (2012)
Walterinnesia morgani	33.12853° N	46.12011° E	Ilam, Ilam Province	Gholamifard and Rastegar-Pouyani (2012)
Walterinnesia morgani	31.96033° N	49.28193° E	Masjed Soleyman, Khuzestan Province	Farzanpay (1989); Gholamifard and Rastegar-Pouyani (2012)
Walterinnesia morgani	28.90117° N	50.83317° E	Bushehr Province	Gholamifard and Rastegar-Pouyani (2012)
Walterinnesia morgani	27.38805° N	56.75916° E	Hormozgan Province	Gholamifard and Rastegar-Pouyani (2012)
Walterinnesia morgani	33.99746° N	45.48072° E	Naft Shahr, Kermanshah Province	Nilson and Rastegar-Pouyani (2007)
Walterinnesia morgani	29.6354° N	51.64126° E	Kazeroun, Fars Province	Farzanpay (1989)
Walterinnesia morgani	33.12361° N	46.1669° E	Mehran, Ilam Province	Fathinia et al. (2010)
Walterinnesi	27.474	53.052	Varavi City, Fars	Field trip

a morgani	44° N	78° E	Province	
Walterinnesia morgani	27.4661° N	53.06055° E	Varavi City, Fars Province	Field trip
Walterinnesia morgani	27.47° N	53.05916° E	Varavi City, Fars Province	Field trip
Walterinnesia morgani	27.51305° N	52.92944° E	Tabnak Gas Field, Lamerd, Fars Province	Field trip
Walterinnesia morgani	28.35972° N	54.5411° E	Haji Tahereh village, Fars Province	Field trip
Walterinnesia morgani	32.61472° N	48.5075° E	Qaleh-ye Shadab, Khuzestan Province	Field trip
Walterinnesia morgani	33.15111° N	47.72111° E	Pol-e Dokhtar, Lorestan Province	Field trip

Table 2. Summary for selecting the best model for species distribution maps of *W. morgani* via *kuenm* package.

Species	All candidate models	Statistically significant models	MaxEnt features	AICc	wAICc	Delta AICc	AUC	Mean AUC ratio
W. morgani	1054	1054	linear, quadratic, product	418.125	0.169	0.00	0.955±0.014	1.866

AICc: A corrected AIC score, used for a small sample size by increasing the cost for each parameter.

wAICc: The model weight is the relative likelihood for each model, divided by the total relative likelihood for all models that were considered.

Delta AICc: The difference between the model with the lowest score (the “best” model) and the AICc score for each model.

AUC: Area under the curve is a measure of the accuracy of the model.

Mean AUC ratio ≥1.00, $p<0.05$ means predictions are significantly better than a random model

Table 3. Percentage contribution of the environmental layers used in species distribution modeling of *Walterinnesia morgani*.

Species	Bio 2	Bio 7	Bio 9	Bio 14	Bio 15	Bio 17	d_river	Elev
W. morgani	10	4.3	27.7	0.4	14.7	1.1	31.9	10

Figure 1. An adult individual of *Walterinnesia morgani* from Fars Province, southern Iran.

Figure 2. A juvenile specimen of *Walterinnesia morgani* from Fars Province, southern Iran.

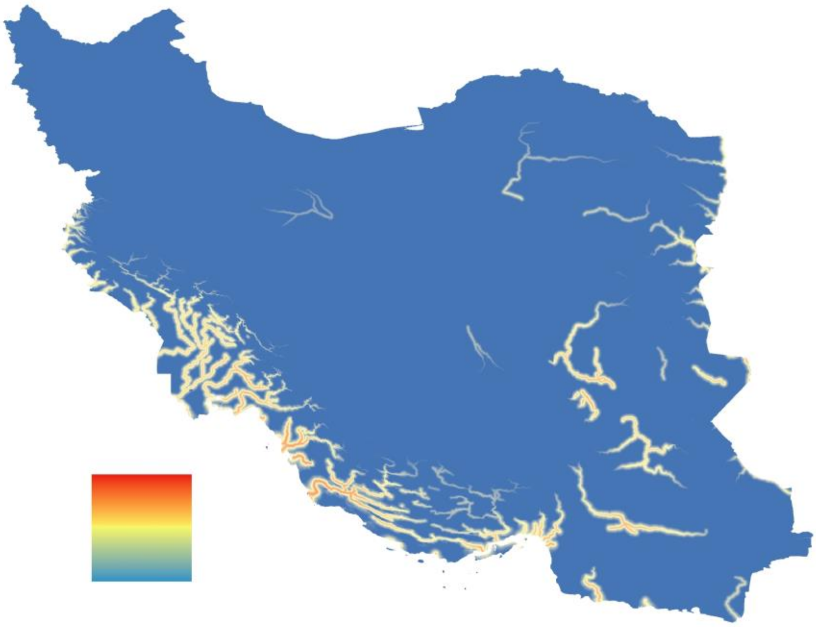

Figure 3. Recent historical habitat suitability of *Walterinnesia morgani* in Iran (warmer colors refer to high suitability level).

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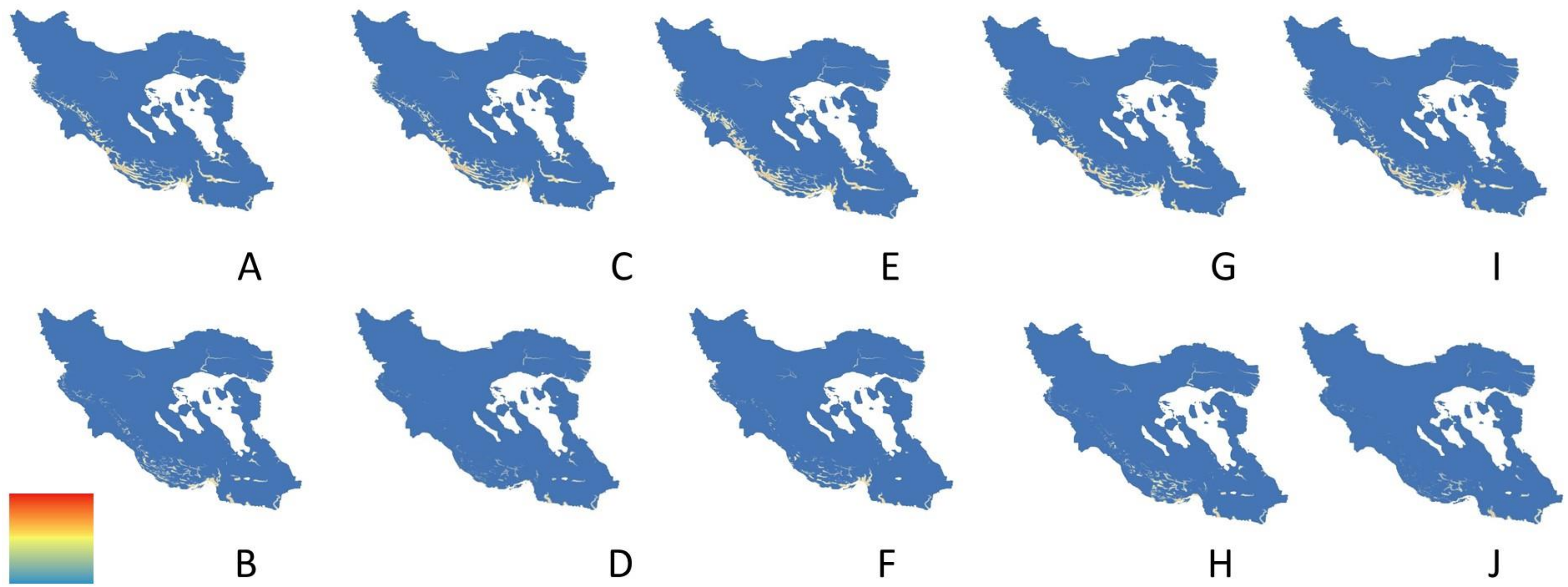

Figure 4. Future habitat suitability (2081–2100) of *Walterinnesia morgani* in Iran based on **A.** GFDL-ESM4 under optimistic scenario (ssp 126). **B.** GFDL-ESM4 under pessimistic scenario (ssp 585). **C.** IPSL-CM6A-LR under optimistic scenario (ssp 126). **D.** IPSL-CM6A-LR under pessimistic scenario (ssp 585). **E.** MPI-ESM1-2- HR under optimistic scenario (ssp 126). **F.** MPI-ESM1-2- HR under pessimistic scenario (ssp 585). **G.** MRI-ESM2-0 under optimistic scenario (ssp 126). **H.** MRI-ESM2-0 under pessimistic scenario (ssp 585). **I.** UKESM1- 0-LL under optimistic scenario (ssp 126). **J.** UKESM1- 0-LL under pessimistic scenario (ssp 585) (warmer colors refer to high suitability level)