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An integrative climate and land cover change detection unveils extensive range contraction in mountain newts

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ABSTRACT

The global decline of amphibian populations, driven by anthropogenic activities, is a pressing conservation issue, with salamanders being of particular concern, as these species serve as ecological indicators vulnerable to environmental change. Mountain newts of the *Neurergus* genus, which are endemic to the Zagros Mountain chain from southeastern Turkey to northern Iraq and southwestern Iran, face a multitude of threats. Among these threats, climate change and land use alterations have been identified as major contributors to the decline of these species. Given the varying spatiotemporal scales at which these factors operate, in this study we aimed to assess the impacts of climate and land use/land cover (LULC) changes (LULCC) on the distribution of the *Neurergus* genus. We employed MaxEnt model to predict their habitat suitability under current climatic conditions. We projected the predicted model to the future, i.e., 2050, under two climate change scenarios. We then proceeded to map the LULC patterns of the identified suitable habitats for each species using Landsat satellite images, and conducted a hindcast of LULCC within these habitats for three time-slices 1988, 2005, and 2020. Finally, we evaluated the efficiency of current network of protected areas (PAs) and key biodiversity areas (KBAs) in Iran, Iraq, and Turkey to cover suitable habitats of the species. Our results revealed that climate changes would negatively influence all *Neurergus* species, with southern species in Iran and Iraq, i.e., *N. derjugini*, *N. kaiseri*, and *N. crocatus* exhibiting the greatest range loss. Conversely, LULC change detection indicated that northern species in Turkey, i.e., *N. strauchii* and *N. barani*, are more exposed to cropland developments and have experienced greatest habitat changes over the past 30 years. Ultimately, our findings underscore the insufficiency of extant conservation areas in protecting *Neurergus* habitats and urge the need for comprehensive conservation measures. We recommend promoting less strictly conserved areas, e.g., KBAs, implementing trans-boundary conservation plans, and designating new reserves to ensure long-term preservation of amphibians in the regions.

1. Introduction

Amphibians as the indicator species of their natural ecosystem are exposed to various threats caused by unsustainable human activities (Nori et al., 2015; Blaustein, 2010). Due to their permeable skin, shell-less eggs, aquatic-terrestrial transient life cycles and ectothermic lifestyles, amphibians are strongly sensitive to changes in environmental condition (Hof et al., 2011; Stuart et al., 2004).

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Unfortunately, global amphibians' population have been steadily decreasing over the past few decades, with the highest proportion of threatened species among terrestrial vertebrates (Stuart et al., 2004; Blaustein, 1994). Despite this, conservation efforts on a global scale have yet to adequately address the conservation needs of these vulnerable animals. Furthermore, the "extent of occurrence" of many amphibians have limited overlap with protected areas (Rodrigues et al., 2004; Venter et al., 2014). Among the amphibians, salamanders due to their irresistible dependence on water resource and limited dispersal ability are more sensitive to environmental changes, and thus, are exposed to highest risk of extinction (Price et al., 2011). Additionally, salamanders' persistence is broadly influenced by humidity and temperature, hence, their geographical distribution range will be strongly affected by the future climate change (Hof et al., 2011). Generally, distribution of the species in an area is affected by their dispersal ability and limited factors such as interactive relationships with other species (biotic factors) and features of the landscape (abiotic factors). However, almost all species have been experiencing anthropogenic changes in environmental conditions, such as LULCC and global warming, leading to interference in their habitat selection pattern (Piha et al., 2007; Nori et al., 2015). In addition, the combined influences of climate and LULCC contribute to contraction in the extant of suitable habitats, reduction in population size, limited gene flow, decrease the resistance and ultimately increase the risk of species extinction (Marshall et al., 2018; Blaustein et al., 2010).

The mountain newts of the genus *Neurergus* (Cope, 1862) are endemic to the Zagros Mountain chain across western Iran, northern Iraq, and southeastern Turkey. This region is an important center of endemism in the Irano-Anatolian Hotspot, one of 36 global biodiversity hotspots, which is characterized by high numbers of irreplaceable and vulnerable species and require urgent conservation action (Myers et al., 2000; Noroozi, 2019). The *Neurergus* genus includes five rare and range-restricted species: Lorestan newt or Emperor spotted newt (*N. kaiseri*), Kurdistan newt (*N. derjugini*), yellow-spotted newt (*N. crocatus*), and Anatolian newts (*N. strauchii* and *N. barani*). All of these species are threatened, with the Kurdistan newt listed as Critically Endangered and others as Vulnerable in the IUCN Red list. Local populations of these species have declined significantly over recent decades (Rancilhac et al., 2019; Goudarzi et al., 2019). In Iran, Iraq, and Turkey habitat destruction caused by over-grazing at highlands, land use changes, and water extraction from streams are the main threats to the species (Goudarzi et al., 2019; Khwarahm et al., 2021). Also, illegal collecting for the pet trade and dam construction in Iran and Turkey poses significant threats to these species (Sharifi et al., 2008). In particular, dam construction facilitates the dispersal of predators such as cyprinid fish (*Barbus* sp.) into upland streams where they would not normally be found; further endangering these already threatened newts (Sharifi et al., 2008).

On a larger scale, due to their limited dispersal abilities and narrow range of tolerance, global warming will have a significant impact on newts of the *Neurergus* genus that inhabit mountainous areas. According to Parmesan (2006) species living polar and mountainous regions are generally the most vulnerable to climate change. The primary concern in this regard is the limited dispersal capability of the *Neurergus* genus, which hinders their ability to shifts their distribution and adapt towards rapid pace of global warming. Consequently, there is a risk of these species becoming extinct in the near future. Furthermore, the newts belonging to this genus are exclusively found in the border regions of Iran, Turkey and Iraq. The natural resources in these areas have been directly and indirectly impacted by the destructive effects of war (Beygi et al., 2020). Moreover, previous studies have shown significant changes in land use and land cover in these regions due to the activities of local people for their livelihood requirements such as deforestation for livestock grazing, fuel supply and other necessities. These changes have led to a significant reduction in the Zagros forests and the destruction of its integrity (Henareh Khalyani et al., 2012; Beygi Heidarlou et al., 2020).

Ecological niche modeling (ENM), or species distribution modeling (SDMs), is an operational tool used to assess the impact of environmental changes on species distribution. SDMs help estimate ecological niche boundaries, investigate habitat suitability, and identify geographical distribution patterns (Phillips et al., 2006; Guisan et al., 2013). Combining remote sensing with SDM techniques can provide valuable insights into the habitat quality, resilience, and threats faced by endemic and/or threatened species (Vila-Viçosa et al., 2020). Land cover and land use changes can be effectively highlighted using remote sensing, while the quantification of climate change impacts on habitat suitability serves conservation purposes at a larger scale (Guisan et al., 2013).

Due to the distinctive distribution and endemism patterns observed among salamanders of this genus, along with their vulnerability to environmental changes, numerous research endeavors have been undertaken to evaluate the habitat suitability of these species, and especially, their responses to climate change (Sharifi et al., 2017; Goudarzi et al., 2019; Khwarahm et al., 2021; Ebrahimi & Ahmadzadeh, 2022). The majority of these investigations have predominantly concentrated on individual species, without previous attempts to conduct comparative habitat modeling or to assess variability across the entire genus. Moreover, these studies have predominantly emphasized climatic factors, thereby neglecting an examination of changes in land use within the habitats of these species. In this study we aimed to investigate the impact of changing environmental conditions on the distribution of *Neurergus* at both global (climate change) and local (land use change) scales. By employing SDMs, we assessed the effects of climate change on the species' suitable habitats. Additionally, we detected LULC changes to evaluate the influence of local changes on the resistance of these species. To the best of our knowledge, this integrated approach, combining climate change and LULC assessments, has rarely been utilized in biodiversity risk assessments. The adoption of this approach offers a valuable opportunity to identify species that are more vulnerable and prioritize them for effective conservation planning. By incorporating both global and local scales, our findings contribute to a comprehensive understanding of the threats faced by *Neurergus* species and emphasize the need for proactive conservation measures.

2. Methods

2.1. Study areas and species data

Mountain newts of the genus *Neurergus* (Cope, 1862) occur in Zagros mountain-range of western Iran, northern Iraq and eastern and southeastern Turkey (Noroozi, 2019). This study covers an area of 391,686 km^2 with an altitude range of –5–4000 m encompassing the Irano-Turanian biogeographical region and two global biodiversity hotspots: Irano-Anatolian and Caucasus (Myers et al., 2000; Noroozi et al., 2019). To obtain sufficient data of the *Neurergus*'s presence, we reviewed most of the relevant scientific literatures about their geographic distribution along with data of the Global Biodiversity Information Facility (GBIF) database (https://www.gbif.org). Specifically, we reviewed 94 published papers and two atlases of the amphibians of the region (see Table S2 of the Supporting Information for more details of the scientific resources). Altogether, 766 presence points were collected as follows: *Neurergus barani* n = 52, *Neurergus strauchii* n = 160, *Neurergus crocatus* n = 81, *Neurergus derjugini* n = 211, and *Neurergus kaiseri* n = 262 (Fig. 1). To minimize sampling bias effect in our dataset caused by spatial autocorrelation of presence points in clumped areas (Ahmadi et al., 2023), we adopted a spatial filtering approach. We spatially filtered presence points of all species within a 1-km radius buffer around them, based on the dispersal abilities of *Neurergus* species (Afroosheh et al., 2014), by using "SpThin" package in R environment. We integrated two main procedures to assess the effects of environmental changes on the distribution of the genus *Neurergus*. We first used the MaxEnt model to predict suitable habitats of the species based on the current and future climatic conditions. We then based the current suitable habitats of the species and performed a hindcast of LULCC within their habitats over the past 30 years, considering three time slices: 1990, 2005, and 2020 (see below).

2.2. SDM analysis

In our large-scale study, we focused on the climatic variables that are crucial for the persistence of Amphibians in current and future conditions (D'Amen et al., 2011). We obtained 19 climatic variables from the WorldClim database (https://www.worldclim.org/), including seasonal, monthly, and annual temperature and precipitation values, with a pixel size of 30 arc-seconds (~1 km). To address

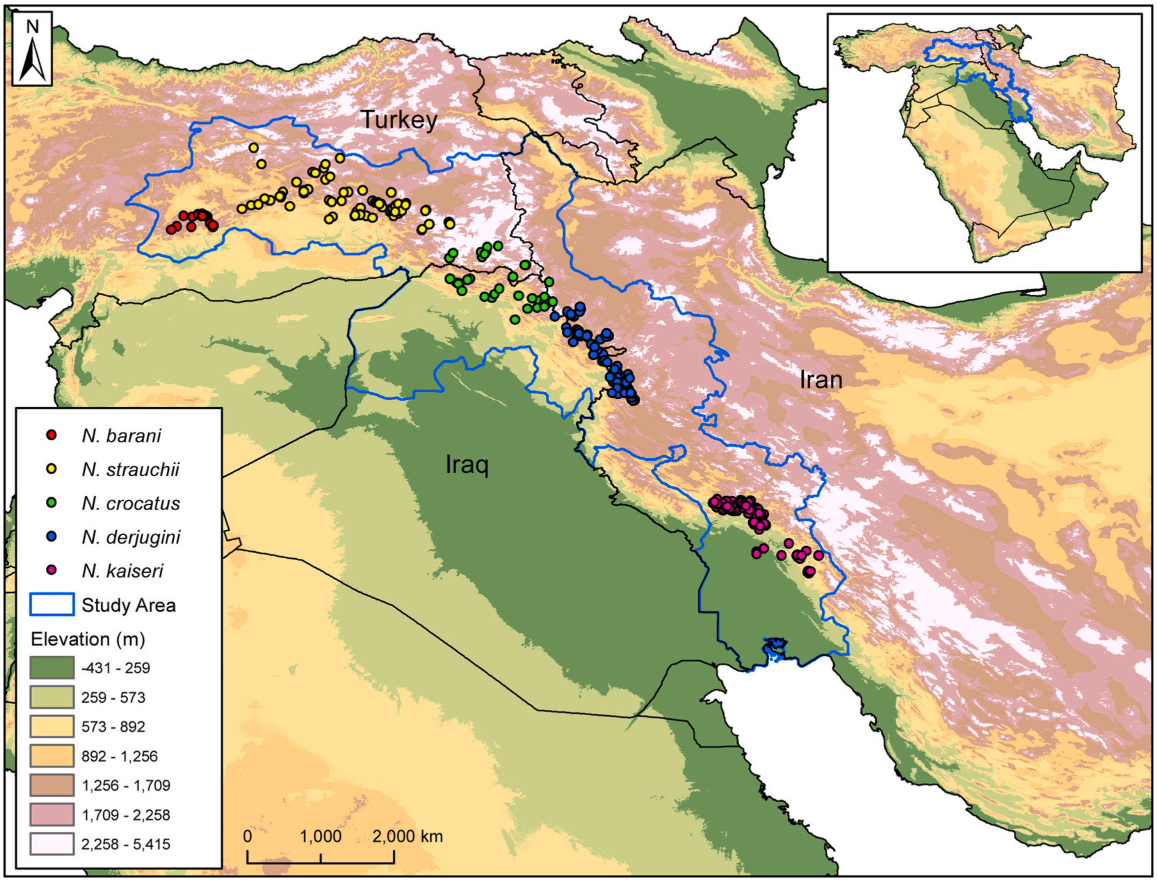

Fig. 1. Geographical distribution of *Neurergus* species across Zagros Mountain range from southeastern Turkey to southwestern Iran.

multicollinearity among the climatic variables, we calculated the Variance Inflation Factors (VIF) using the usdm package (Naimi et al., 2015). Variables with VIF <6 were retained for the SDM analysis.

We employed the maximum entropy (MaxEnt) method to model the species' distribution under current and future climate change scenarios. MaxEnt was chosen because it does not require absence data and performs well with small sample sizes (Wisz et al., 2008). It has also been shown that MaxEnt outperforms other models, including ensemble approaches and/or when using incomplete input data (Valavi et al., 2022; Ahmadi et al., 2023). Since default settings may not be optimal for different SDM attempts (Muscarella al, 2014), it is recommended to parameterize SDMs and seek a fine-tune model based on the input data (Ahmadi et al., 2023). Two important settings in the MaxEnt model are feature classes (FC), which define constraints, and regularization multiplier (RM), which balances model fit and complexity (Phillips et al., 2006). In this study, we used the "ENMeval" package (Muscarella et al., 2014) to fit a well-performing distribution model for each *Neurergus* species.

To select the optimal MaxEnt model, we considered six feature types (L, LQ, H, LQH, LQHP, and LQHPT) and three RM values (0.5, 1, 2). We selected 5000 background points within a 100-km buffer around the presence points of each species. The MaxEnt model was repeated using a spatial cross-validation procedure with five spatial blocks. The best-fitted model was chosen based on the Akaike information criterion (AICc), selecting the model with the lowest delta AICc value (delta AICc = 0). We converted the continuous MaxEnt models to binary presence/absence maps using a threshold where sum of the sensitivity and specificity of the model was maximum, as recommended by Liu et al. (2013). Sensitivity and specificity were calculated to obtain the true statistic skill (TSS) of the model, defined as TSS = sensitivity + specificity – 1.

For future climate change projections, we used four global circulation models (GCMs): ACCESS-CM2 (Dix et al., 2019), CNRM-CM6–1 (Voldoire et al., 2019), IPSL-CM6A-LR (Boucher et al., 2020), and MIROC6 (Shiogama et al., 2019) for 2050 (average for 2041–2060), under two shared socio-economic pathway scenarios (SSP2–4.5 and SSP5–8.5). This resulted in a total of 40 predictions for each species (5 model iterations × 4 GCMs × 2 climate change scenarios). We employed raster calculator analysis for each SSP scenario to compute the average climatic suitability maps obtained from four GCMs. Predictive models often exhibit reduced reliability when applied beyond their training domain (Elith et al., 2010). This is particularly evident in climate change predictions, where models fitted to current conditions are extended to unexplored future climatic scenarios (Lorestani et al., 2022). To address this challenge, we employed the Multivariate Environmental Similarity Surfaces (MESS) analysis to quantify the similarity between new environments (future climatic conditions) and those in the training sample (Elith et al., 2010). In this study, after projecting climate change, we generated the MESS map and utilized negative MESS values, representing dissimilar areas, to crop the future projections. To assess the effects of climate change on the potential distribution of *Neurergus* species, we calculated the percentage of habitat loss and gain for each GCM and SSP scenario. Habitat gain was determined by the number of pixels predicted to become suitable in the future but currently unoccupied, while habitat loss was determined by the number of pixels currently suitable but predicted to become unsuitable in the future.

2.3. Land use / land cover analysis

We performed LULC hindcasting by detecting changes in cover types within the species' suitable habitats, comparing the current time (2020) with the past time slices (2004 and 1988). To this end, for each species suitable habitats were considered based on the identified binary suitable habitats from the previous stage. We based our LULC classification on atmospherically corrected images of Surface reflectance Tier 1, 2, which included two Landsat 5 (TM; Thematic Mapper) satellite images for the year 1988 (01/01/1988–01/01/1989) and 2004 (01/01 /2004–01/01/2005), and a Landsat 8 (OLI; Operational Land Imager) satellite image for the year 2020 (01/01/2020–01/01/2021). For each period, satellite images of 12 months of the year were downloaded and the median of 12 images was used to extract the LULC map. We focused on six LULC categories including cropland, dense forest, woodland (low-density forest, shrubs, and scrublands), sparse vegetation, urban areas, and water, to classify satellite images. We only considered these categories because collecting field data on a broad scale is a very difficult and time-consuming task. Based on the objectives of the research and intended LULC categories, training samples were selected based on the visual interpretation of satellite images in the Google Earth Engine environment. Also, due to the appropriate quality of images in Google Earth software for the years 2004 and 2020, this platform was also used to select training points. In addition to the original Landsat spectral bands Blue, Green, Red, Near Infrared (NIR), and Shortwave Infrared (SWIR), we also produced the Normalized Difference Vegetation Index (NDVI) band to be used in our LULC classification. The accuracy of the input data, here our training samples, plays an important role in the final accuracy of the classified images (Turner et al., 2003). Thus, prior to the final classification, we conducted a quality assessment of the training samples using the time-series of the 12 NDVI bands generated for each time period. We used Self Organizing Maps (SOM) method developed in the sits package (Simoes et al., 2021) in R environment for the quality control and detecting noisy samples. SOM is an innovative method to assess the quality of each training sample by reducing image time series dimensionality (Kohonen, 1990). In this method two-dimensional mapping is employed to transform high-dimensional data, while preserving the topological relations among similar patterns (Simoes et al., 2021). During the projection of a high-dimensional training sample dataset onto a 2D self-organizing map, the map's units, also known as "neurons," engage in a competitive process for each sample. The resulting map will exhibit close proximity between high-quality samples belonging to the same LULC category. Accordingly, neurons associated with the same LULC class are expected to form a cluster in the SOM map. With the use of this quality control method we were able to detect outlier neurons located far from their label cluster and remove those noisy data from the LULC classification procedure. In our case, we used monthly NDVI time-series for the years 1988, 2004, and 2020, and generated their SOM maps based on a 10 × 10 grid map. After assessing the quality of training samples and removing noisy data, we used 70 % of the remaining samples for training LULC classification and used the remaining 30 % for testing the model. For each species, LULC classification was implemented within the GEE environment based on the random forest (RF) machine learning model. RF was chosen for its higher performance, increased accuracy, and simpler calculations compared to other pixel-based approaches (Pal, 2005). We used overall accuracy (OA) and kappa coefficient to assess our modeling performance. Both these methods determine the probability of correct classification with a random selection of a location from the classified image. The distribution of amphibians is influenced by LULC pattern in both micro and landscape scales (Sutton et al., 2023). Therefore, in addition to the entire suitable habitats of the species, we also assessed LULCC within a buffer zone of 500-meter radius around their presence points.

2.4. Conservation gap analysis

We calculated the amount of spatial overlap between the obtained habitat suitability of *Neurergus* species with the network of conservation-oriented areas in Iran, Turkey, and Iraq. To do so, we obtained most recent polygons of protected areas (PAs) from Iran's Department of Environment (DoE), Turkey's Ministry of Environment and Urbanization, The World Database on Protected Areas (WDPA available on http://protectedplanet.net), and Key Biodiversity Areas (KBAs available on https://www.keybiodiversityareas.org/). We then intersected the binary habitat suitability map of the species with the conservation-oriented areas in the ArcMap 10.5.

3. Results

3.1. Climate change analysis

Predictive performances of the MaxEnt model for all species showed AUC and TSS scores higher than 0.9 and 0.85, respectively, which indicated the excellent performance of the models (Table 1). Two top variables with highest contributions in the MaxEnt model of the species were identified as follows; *N. barani*: precipitation of driest month (BIO14, 56.2 %) and temperature annual range (BIO7, 15.1 %), *N. strauchii*: precipitation of driest month (45.4 %) and precipitation of wettest month (BIO13, 44.8 %), *N. crocatus*: precipitation of wettest month (48.9 %) and the Isothermality (BIO3, 27.2 %), *N. derjugini*: precipitation of wettest month (44.8 %) and mean temperature of wettest quarter (BIO8, 22.2 %), and *N. kaiseri*: precipitation of driest month (30.5 %) and the precipitation of wettest month (22.1 %; Table 1). Density plots of the climatic variables showed similar distribution patterns of *N. barani*, *N. strauchii*, and *N. kaiseri* along four climatic variables including BIO3, BIO4, BIO7, and BIO8 (Fig. 2). *N. derjugini* showed most distinct distribution especially along climatic gradients of BIO3, BIO4, and BIO8.

The projected impacts of future climate change (year 2050) indicated that *N. derjugini* is likely to experience the greatest range loss (78 % and 92 % under SSP2–4.5 and SSP5–8.5, respectively) followed by *N. crocatus* (73 % and 90 % under SSP2–4.5 and SSP5–8.5, respectively) (Table 2, Fig. 3). For *N. kaiseri* and *N. barani* habitat loss was projected to be around 35 % under SSP2–4.5 and nearly 50 % under SSP5–8.5. We found that *N. strauchii* would probably experience the lowest range loss (18 % and 19 % under SSP2–4.5 and SSP5–8.5, respectively). Interestingly, our results indicated that there would be no significant range gain for any of the *Neurergus* species (Table 2). The Altitudinal shift analysis revealed that all the species will probably experience range shift toward higher habitats compared to current time. The highest upward shift was observed for *N. derjugini* (695 m) and *N. crocatus* (610 m), respectively, both under SSP5–8.5. *N. strauchii* (70 m) and *N. barani* (120 m) projected to experience the lowest upward range shift, respectively, both under SSP2–4.5 (Table 2).

3.2. LULC change detection

3.2.1. Results of the SOM analysis

The SOM grid map was employed to enhance the quality of the training samples in this study. The SOM maps of 10 × 10 grid size indicated that cropland class exhibited the highest between-class confusion for all three periods. Fig. 4 shows SOM of the year 2020. Between-class confusion of all three periods and SOM grid maps of 1988 and 2004 are provided in the Supporting Information. Overall, training samples belonging to *N. barani* and *N. strauchii* distribution ranges showed higher levels of impurity (Fig. S1, Table S1). The mean purity values for water, urban, woodland, and cropland classes were above 90 %, 85 %, 80 %, and 70 % respectively. The analysis revealed that the greatest confusions occurred between cropland, woodland and sparse vegetation classes (Table S1, Supporting Information).

Table 1
Predictive performance and variables relative importance in the climatic suitability model of the *Neurergus* species. Score are the average of 10 cross-validated repetitions.

Species	AUC	TSS	BIO3	BIO4	BIO7	BIO8	BIO13	BIO14
N. barani	0.98	0.91	8.9	3.5	5.9	17.6	27.9	36.2
N. strauchii	0.96	0.89	42.8	1.3	2.9	2.9	42.8	42.8
N. crocatus	0.94	0.85	13.8	37.5	37.5	37.5	12.2	37.5
N. derjugini	0.98	0.92	2.4	7.8	1.4	44.9	36.3	7.8
N. kaiseri	0.98	0.93	16.9	11.3	0.2	5	40.1	26.6

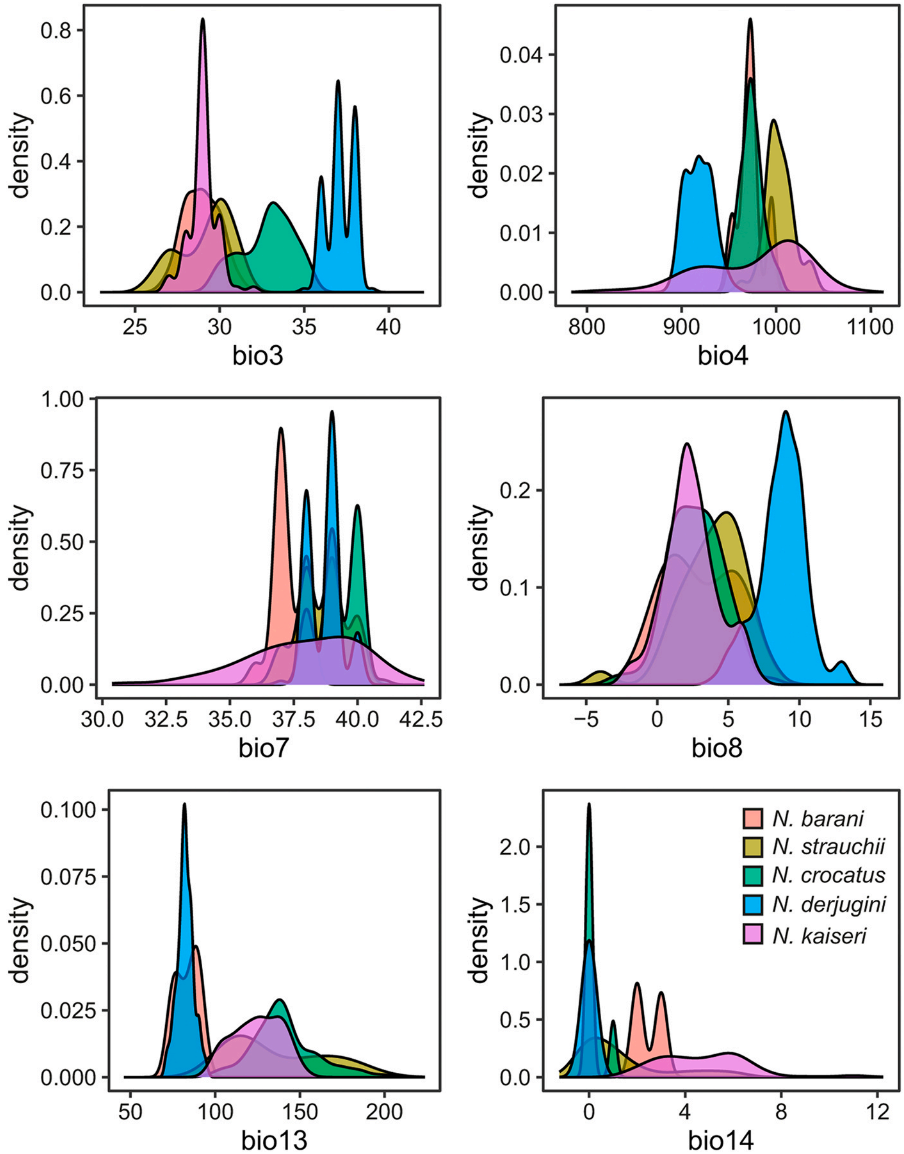

Fig. 2. Density plot of the climatic variables indicating univariate climatic niche of the *Neurergus* species.

Table 2
Average range changes (in percent) and mean upward range shift (in meters) in suitable habitats of *Neurergus* species under SSP2–4.5 and SSP5–8.5 scenarios in 2050.

	2050 – SSP2-4.5			2050 – SSP5-8.5		
	Contraction	Expansion	upward shift	Contraction	Expansion	upward shift
N. barani	34	0	120	48	0	125
N. strauchii	18	5	70	19	2	74
N. crocatus	73	0	582	90	0	610
N. derjugini	78	0	650	92	0	695
N. kaiseri	35	0	280	50	0	326

3.2.2. LULCC across the entire suitable habitats

The overall accuracy and kappa coefficient of the image classification for the three time-periods were above 80 % for all species. The highest and the lowest overall accuracy and kappa coefficient were obtained for *N. crocatus* and *N. barani,* respectively (Table 3).

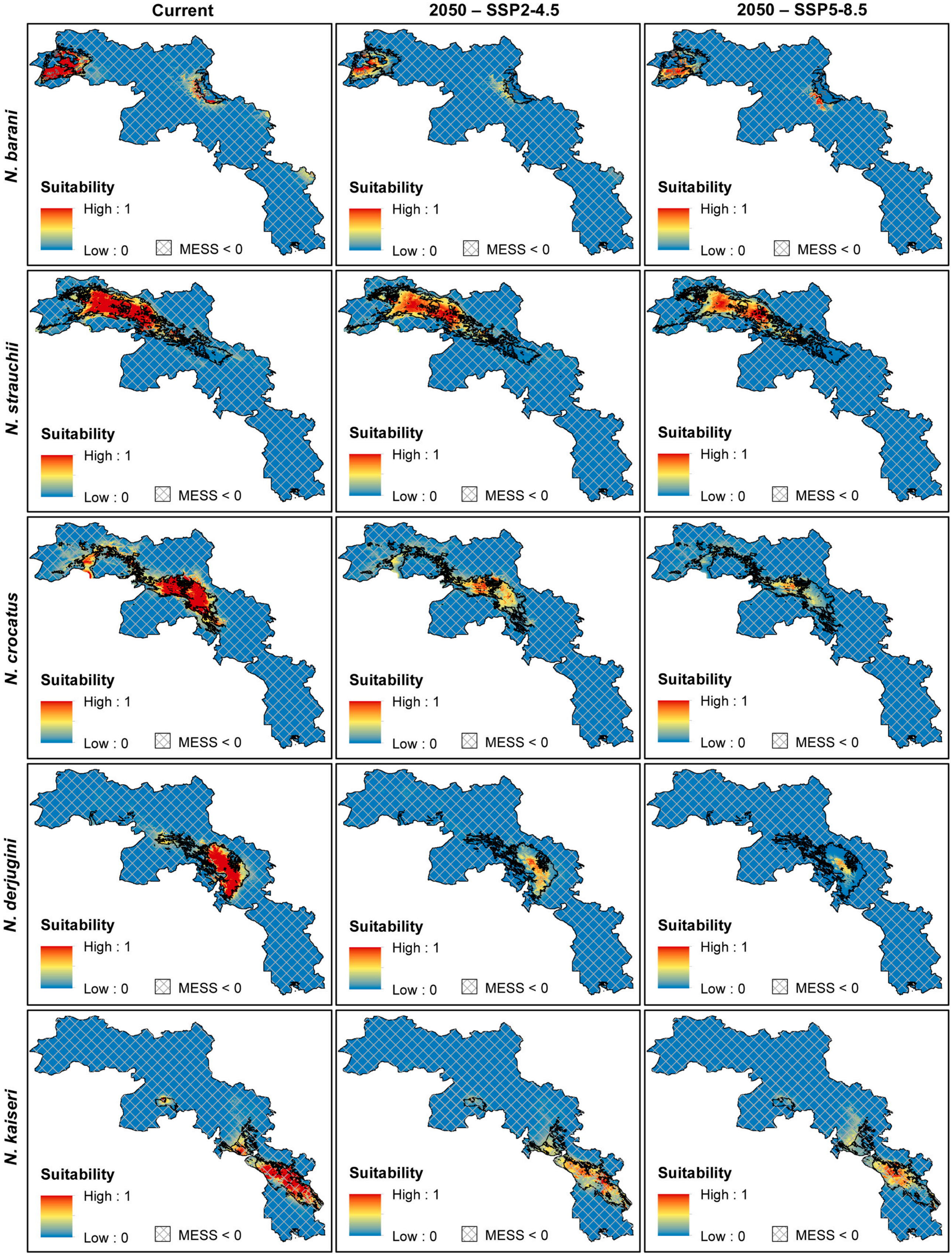

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Fig. 3. Habitat suitability of *Neurergus* species under current and future climate change scenarios. Dashed lines indicate dissimilar areas with multivariate environmental similarity surface (MESS) less than zero.

The LULC maps depicting the climatic suitability areas for *Neurergus* species in 1988, 2004, and 2020 are presented in Fig. 5. For *N. barani* and *N. strauchii*, suitable habitats in 1988 primarily consisted of cropland and sparse vegetation. For this species, there has been an increase in the proportion of cropland over time, which accounted for 12 % in 2004 and 7 % in 2020 (Fig. 6). For *N. crocatus* woodland was the dominant land type, occupying approximately 30 % of the total suitable areas. For this species, the overall change in vegetation cover was relatively small, with a 13 % decrease from 1988 to 2004 and a subsequent 15 % increase from 2004 to 2020 (Fig. 6). In the case of *N. derjugini*, cropland and woodland accounted for more than 15 % and 20 % of the most suitable areas,

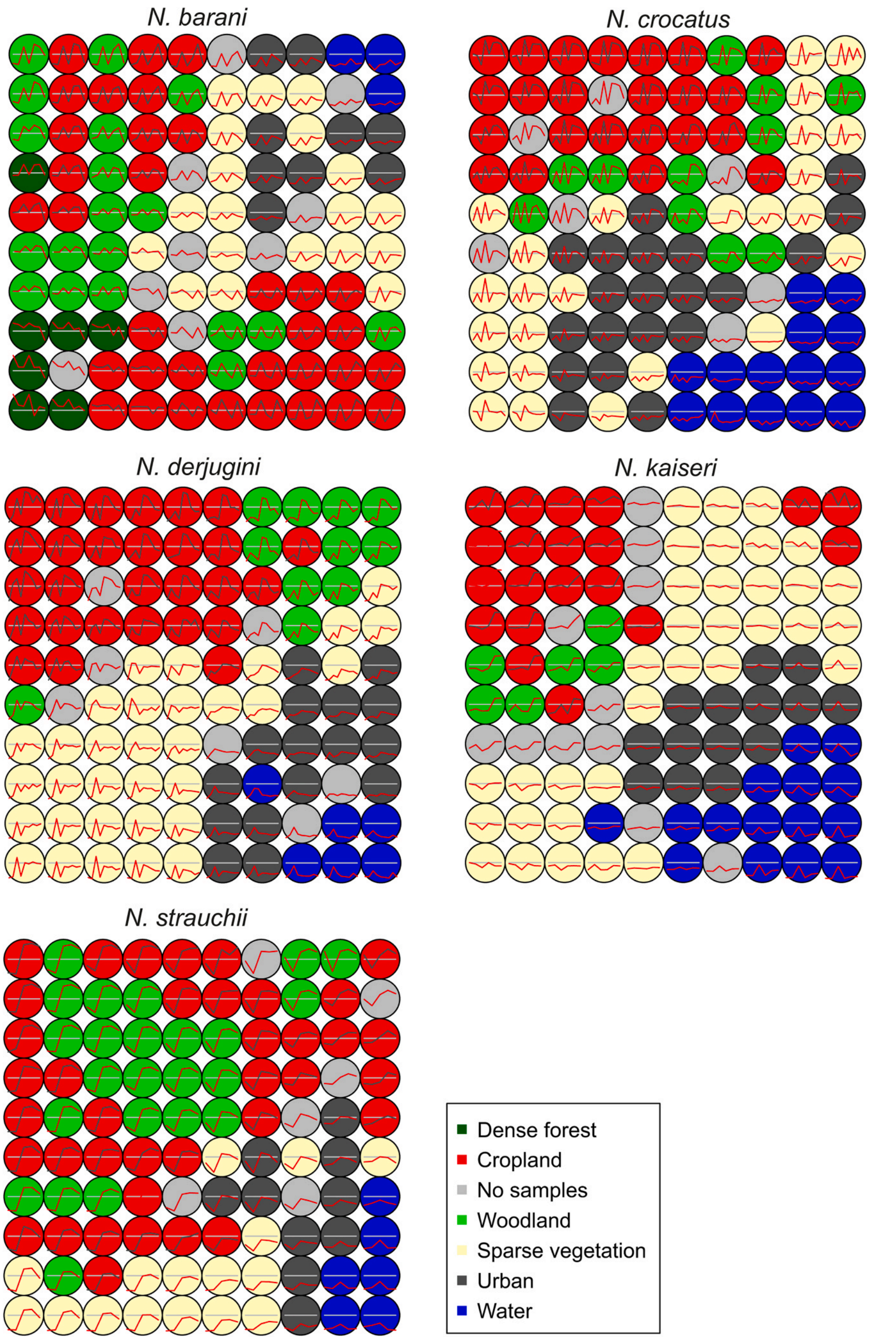

Fig. 4. SOM grid of monthly NDVI time-series for the year 2020 used for quality control of the training samples.

Table 3
Overall Accuracy and kappa coefficient of land use/land cover (LULC) classifications.

Species	1988		2004		2020	
	Kappa	OA	Kappa	OA	Kappa	OA
N. barani	0.869	91.44	0.794	80.45	0.783	82.57
N. strauchii	0.829	89.03	0.836	92.25	0.868	91.44
N. crocatus	0.942	95.87	0.924	96.55	0.920	94.72
N. derjugini	0.907	95.65	0.936	95.48	0.936	94.03
N. kaiseri	0.913	93.87	0.931	94.78	0.909	95.81

respectively. Cropland remained relatively stable from 1988 to 2020, while woodland cover experienced a 5 % increase from 1988 to 2004 followed by a 9 % decrease from 2004 to 2020. Woodland was the dominant land cover in the suitable habitats of *N. kaiseri*, and there were no significant changes for this cover type from 1988 to 2020. It is worth noting that the urban areas within the climatically suitable habitats of all *Neurergus* species has increased significantly from 1988 to 2020. Regarding the presence of large water bodies within the suitable areas, *N. crocatus* and *N. kaiseri* experienced a decrease initially followed by an increase, from 1988 to 2020, while *N. derjugini* and *N. strauchii* exhibited the opposite trend (Fig. 5 and Fig. S3).

3.2.3. LULCC in the 500-meter buffer around the presence points

The analysis of LULCC within the 500-meter buffer around the presence points yielded different pattern for the species (Fig. 6). For *N. barani*, the percentage of woodland increased by 1.57 % from 1988 to 2004 and by 0.34 % from 2004 to 2020. Cropland showed an increase in the first period (20.47 %) and a decrease in the second period (7.55 %), while urban areas exhibited minimal development in both periods. In the case of *N. strauchii*, both cropland and urban areas increased over the two 16-year periods, while woodland decreased. For *N. crocatus*, woodland initially decreased by 10 % and then increased by 13 % in the respective periods. For *N. derjugini*, woodland, cropland, and urban areas showed slight increases (less than 5 %) in both periods. In the case of *N. kaiseri*, no urban areas were observed within the 500-meter buffer around the species' presence points (possibly due to the scale of our study not capturing rural areas). Cropland exhibited minimal development (1 %) only in the second period, while woodland decreased by 4 % in the first period and increased by 8 % in the second period.

3.3. Conservation gap analysis

The results of the gap analysis indicated that suitable habitats of *N. barani* and *N. strauchii* do not overlap with KBAs of the region (mainly in Turkey). Overall, our gap analysis showed that, on average, PAs encompassed a higher percentage of suitable habitats of *Neurerus* species (24.2 %) compared to the PAs (12.75 %). Taking into account both PAs and KBAs, *N. crocatus* showed the greatest conservation overlap followed by *N. derjugini*. Conversely, *N. barani* (1.1 %) and *N. strauchii* (1.2 %) showed the lowest conservation overlap among *Neurerus* species (Table 4). Considering current network of protected areas, we found that conservation representation of *N.barani*, *N. derjugini*, and *N. kaiseri* will be reduced in future climate change scenarios (Table 5). *N. strauchii* showed no change of conservation overlap in the current and future climate change scenarios. Interestingly, the results revealed that conservation representation of *N. crocatus* will continuously increase from current to moderate and extreme climate change scenarios (Table 5).

4. Discussion

The unprecedented climate changes resulting from human activities are a major environmental concern. However, the distribution of this warming is not uniform globally, and different regions and species have varying vulnerabilities to these changes (Parmesan, 2006). Consequently, various species will respond differently to climate change, with some experiencing range contractions while others undergo expansions (Mi et al., 2023). Numerous studies consistently highlight the significant and predominantly adverse effects of climate change on amphibians, which can be attributed to their inherent characteristics (Blaustein et al., 2010; Mi et al., 2023). These effects often contribute to population declines and reductions in geographical ranges (Blaustein et al., 2010; Stuart et al., 2004).

The present study suggests that, except for *N. strauchi*, which may exhibit relatively lower susceptibility to future climate change due to its broader geographical range compared to other *Neurergus* species, the remaining newt species within this genus face significant threats from climate change. Previous studies have also reported a significant decrease in suitable habitats of *Neurergus* species (Ebrahimi & Ahmadzadeh, 2022; Cemal Varol et al., 2016). Additionally, similar to previous research findings (Malekoutian et al., 2021; Vaissi, 2021), our study indicates that these species are likely to undergo shifts in their climatic niches towards higher elevations in response to climate change. Interestingly, our results highlighted that two *Neurergus* species that already occupy higher habitats compared to others, i.e., *N. derjugini* and *N. crocatus*, would likely experience the greatest range loss and upward range shift by 2050. Previous study have similarly indicate that mountain-dwelling species, due their marginal location and narrow niche breadth on temperature gradients, are more vulnerable to climate changes (Abeli et al., 2018; Ahmadi et al., 2019). Being adapted to cooler climates in higher elevations makes them less flexible to changing environmental conditions, and accordingly, with even slight increases in temperature they may struggle to find suitable areas as their habitats shift. For mountain newts, which have limited dispersal

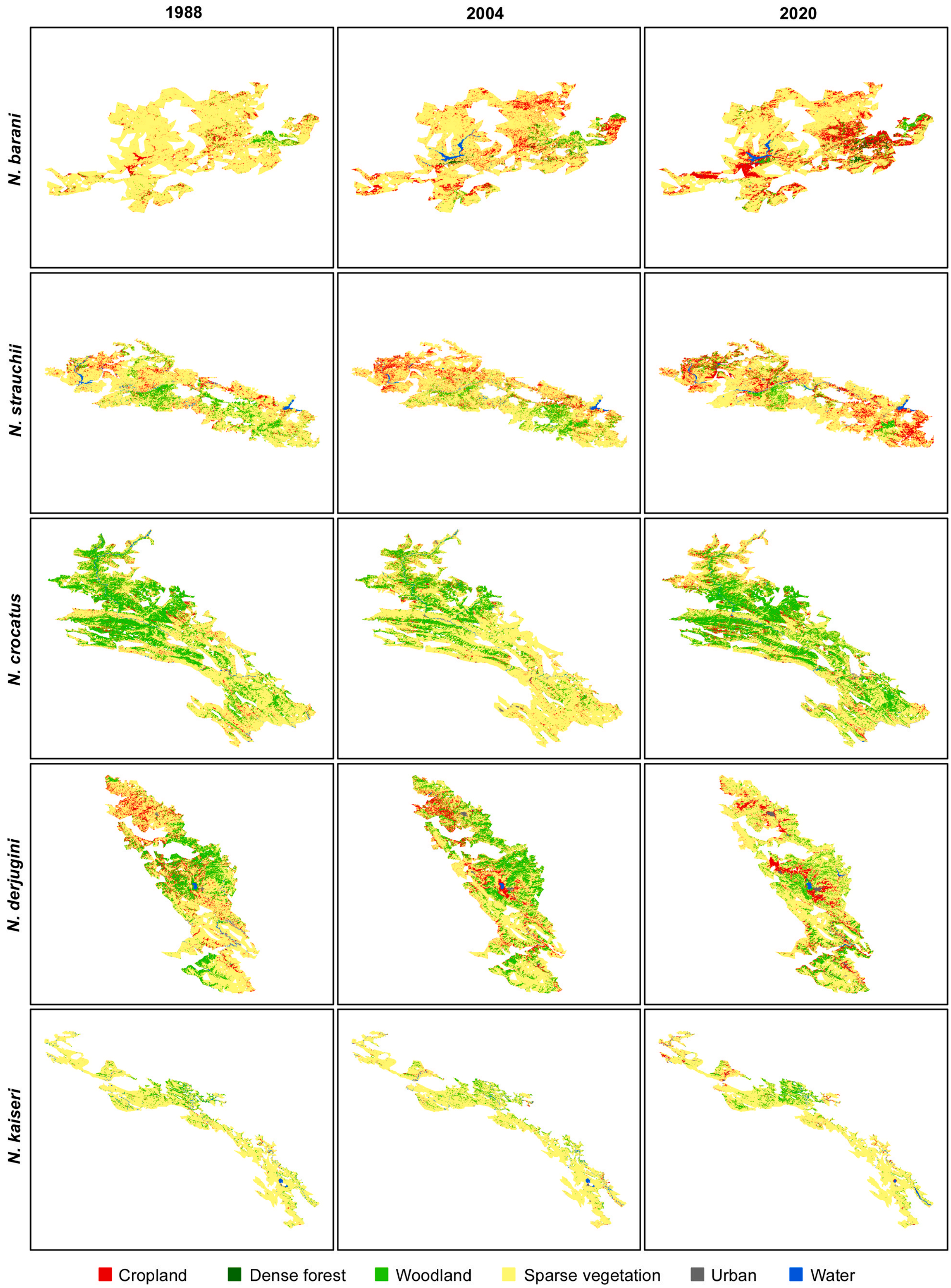

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Fig. 5. Land use / land cover of the *Neurerus* species habitats for 1988, 2004, and 2020.

abilities, this becomes particularly problematic, as they may struggle to migrate to more suitable areas in response to habitat changes. Moreover, the combined impact of climate change and LULCC presents an additional challenge to the long-term survival of amphibians (Price et al., 2011; Nori et al., 2015). Human-induced land use changes lead to habitat fragmentation and degradation, introducing new stressors that further hinder species' capacity to adapt to shifting climatic conditions (Sih et al., 2011).

Regarding the influence of climatic variables on habitat suitability, the precipitation of the driest month was found to be the most influential factor for *N. strauchii*, *N. barani*, and *N. kaiseri*, while the precipitation of the wettest month had the greatest relative impact on *N. crocatus* and *N. derjugini*. This aligns with the findings of Vaissi (2021) and suggests that precipitation is likely the most significant climatic parameter influencing the suitability of habitats for *Neurergus* species due to its close relationship with water availability in their aquatic habitats. Temperature variables representing annual variability, such as isothermality, temperature annual range, and

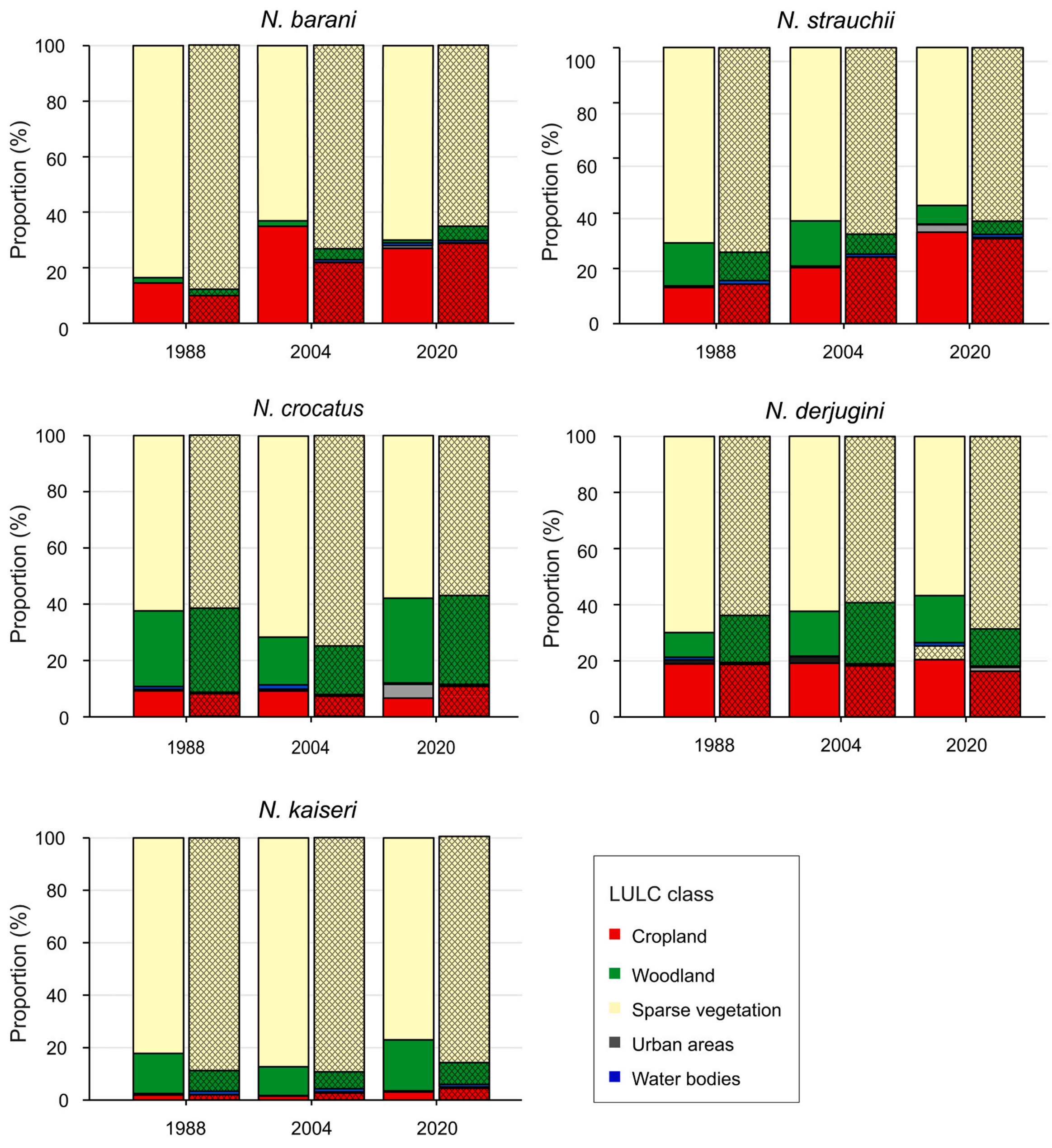

Fig. 6. Results of the LULCC occurred across suitable habitats of *Neurergus* species. Bars with no fill represent LULCC within a 500-m buffer around presence points and those with pattern indicate LULCC within the entire suitable habitats of the species.

Table 4
The extent of spatial overlap between climatically suitable habitats of the *Neurerus* species and the network of protected areas (PAs) and key biodiversity areas (KBAs) of Iran, Iraq, and Turkey.

Species	PAs			KBAs		
	Area (km^2)	Overlap %	Country	Area (km^2)	Overlap %	Country
N. barani	75	1.1	–	0	0	Turkey
N. strauchii	210	1.2	Turkey	0	0	Turkey
N. crocatus	2766	13.3	Iraq	1287	6.2	Iraq & Iran
N. derjugini	703	6.6	Iran	700	6.5	Iraq & Iran
N. kaiseri	149	2	Iran	4	0.05	Iran

Table 5
The extent of spatial overlap between suitable habitats of the *Neurerus* species and network of conservation areas, including both PAs and KBAs, in the current and future climate change scenarios.

	Current		2050 – SSP2-4.5		2050 – SSP5-8.5	
	Area (km^2)	Percentage	Area (km^2)	Percentage	Area (km^2)	Percentage
N. barani	50.20	0.74	22.18	0.32	11.45	0.19
N. strauchii	176.03	1.02	179.12	1.05	181.42	1.1
N. crocatus	4053.92	19.50	2455.57	23.81	1098.16	42.56
N. derjugini	1043.58	9.78	315.12	9.56	0	0
N. kaiseri	153	2.05	125.22	1.75	112.41	1.49

temperature seasonality, were found to have the greatest contribution to the climatic suitability of *Neurergus* species. This highlights the specific dependence of these newts on particular ranges of thermal changes and their narrow ecological niche. Similar findings have been reported by Sharifi et al. (2017) and Ebrahimi & Ahmadzadeh (2022) regarding the significance of temperature in the distribution of newts in Kurdistan.

4.1. LULC analysis

While many studies on species distribution modeling (SDM) of amphibians focus solely on climate factors and overlook the influence of land use, a substantial body of research provides compelling evidence for the importance of land use in determining amphibian habitat suitability (Price et al., 2011; Nori et al., 2015). Landscape composition and arrangement play a crucial role in determining species' future distributions and have significant effects on regional and local climates (Piha et al., 2007). *Neurergus* species are known to predominantly inhabit mountainous regions characterized by rocky and gravel terrain, grasslands, and occasionally trees and shrubs (Afroosheh et al., 2014). The presence of small water bodies, shaded surfaces, and specific land cover types are critical components of their habitat (Sharifi et al., 2008; Goudarzi et. al, 2019).

The analysis of LULC revealed that large water bodies and urban areas have had a relatively small proportion of *Neurergus* habitat compared to other land covers across all three periods (1988, 2004, and 2020). It is important to note that this research was unable to comprehensively identify small water areas, which are of high significance for *Neurergus* persistence (Sharifi et al., 2008). Only large water bodies such as lakes, wetlands, and large dams were identified. The increase in water bodies within the habitat of *N. strauchii*, *N. barani*, *N. derjugini*, and *N. kaiseri* from 1988 to 2004 can potentially attributed to dam construction in the region, which poses a threat to the survival of *Neurergus* species. The disappearance of water sources used by amphibians, forces them to seek new water sources, leading to exploratory behaviors that come with additional costs such as the risk of predation or expending more energy for unexpected movements (Price et al., 2011). Urban growth not only results in the loss and fragmentation of salamander habitats but also leads to pollution and a decrease in the overall health quality of both aquatic and terrestrial habitats, posing further risks to their survival (Price et al., 2011; Sutton et al., 2023).

Cropland accounted for a greater percentage of the species' habitats in Turkey, whereas the habitats of *N. derjugini*, *N. kaiseri*, and *N. crocatus*, the species mainly occurring in Iran and Iraq, were predominantly covered by woodland s (low-density forest and woods). Generally, areas with a long history of agriculture have a negative impact on biodiversity due to the degradation of habitat quality (Piha et al., 2007). Expansions in cropland and urban areas not only increase water consumption and deplete water resources but also pose threats to the health of freshwater ecosystems through land surface disturbances and pollution. These impacts are particularly concerning for amphibians, which are considered indicator species for aquatic ecosystems' health (Hof et al., 2011; Price et al., 2011). Consequently, such disturbances can ultimately lead to the disappearance of amphibian populations (D'Amen et al., 2011; Trochet et al., 2016). Moreover, studies have consistently found a strong negative correlation between land use change and amphibian abundance, highlighting their vulnerability to habitat alterations (Hof et al., 2011; Nori et al., 2015).

Overall, the results of our study indicate that LULC in the habitat of the Anatolian newts experienced more substantial changes compared to other species. While many regions worldwide have experienced a reduction in forest lands in recent decades, Turkey has taken measures to combat deforestation and has increased its forested areas during this period (Butsic al, 2015). For instance, Ersoy Mirici et al. (2020) showed an increase in forests in eastern Turkey, respectively. Moreover, rapid urban growth has been observed in eastern Turkey (Zengin et, 2018) and northern Iraq (Mustafa et al., 2012) in recent decades due to industrial progress and increased immigration. For Iranian newts, priority should be given to the conservation of *N. derjugini* as its habitat witnessed a reduction in woodlands, and *N. kaiseri*, given the increase in croplands. Beygi Heidarlou et al. (2020) revealed a decline in forest cover and an increase in pasture, cropland, and urban areas in the northern Zagros region, which encompasses the habitat of *N. derjugini* and *N. crocatus*. Altogether, human-induced land use change poses a significant threat to all *Neurergus* species, as human development continues to encroach upon their habitats. Furthermore, it is possible that the critical point at which amphibians are impacted by land use changes in our study area has already been exceeded, with minimal changes compared to the substantial climate-driven transformations that have occurred. As a result, our predictions may indicate little effect due to the limited opportunity for land use to influence habitat suitability. However, it is important to note that the impact of land use on the dispersal capabilities of amphibians may become increasingly consequential in the near future, as movement through unsuitable habitat poses a significant risk of mortality for these species (Goldberg and Waits, 2010; Nori et al., 2015).

4.2. Overlap of climate niches of Neurergus species with PAs and KBAs

The findings of this study reveal that KBAs cover a larger area of suitable climatic habitats for *Neurergus* species compared to PAs. This difference can be attributed to the fact that the selection of PAs was not primarily based on rich biodiversity areas (Eken et al., 2016). Our results show that among Iranian *Neurergus* species, *N. kaiseri* exhibits the lowest overlap (2.05 %) with both PAs and KBAs, which aligns with the findings of Ashrafzadeh et al. (2018). Similarly, the Turkish species, *N. strauchii* and *N. barani*, have an overlap of almost 1 % with protected areas. It is worth noting that the suitable climatic habitat of *N. barani* is located near two large protected areas, emphasizing the need for the integration of fragmented PAs. On the other hand, *N. crocatus* and *N. derjugini* appear to be in relatively better conditions compared to other species. However, less than 15 % and 13 % of their suitable climatic habitats overlap with both PAs and KBAs.

Despite the considerable expansion of terrestrial protected areas (PAs) in the recent decade, with a 10 % increase in coverage, there has been a simultaneous rise in the proportion of amphibian species that fall completely outside of PAs. This issue has been extensively discussed within the scientific community (see Diniz-Filho al, 2013; Oliver et al., 2013), highlighting that only a small number of designated PAs effectively safeguard amphibians from the risk of extinction (Rodrigues et al., 2004; D'Amen et al., 2011). Various patterns have been observed in global and regional-scale investigations. D'Amen et al. (2011) highlighted the potential diminishing effectiveness of current PAs in conserving Italian amphibian biodiversity, while Mi et al. (2023) conducted a global assessment indicating that the majority of amphibian and reptile species capable of withstanding the impacts of climate change possess habitats that intersect with the existing network of PAs. However, conservation planning often overlooks the conservation needs of threatened amphibian species, leading to their inadequate representation within PAs (Mi et al., 2023).

Interestingly our gap analysis indicated that while efficiency of conservation areas in protecting suitable habitats of *N. barani*, *N. derjugini*, and *N. kaiseri* will be reduced from current to future climate change scenarios, for *N. crocatus* this pattern is opposite. Although conservation representation of *N. crocatus* seems to be increased, this species, while having the greatest extent of suitable habitats, will also experience the greatest habitat loss and upward range change after *N. derjugini*. The observed pattern primarily arises from the selection of PAs within the region, which typically concentrate on mountainous regions where human development is infeasible (Ahmadi et al., 2020). Furthermore, the designation of PAs in the region primarily targets game species and large-bodied mammals. As global warming continues and species' habitats shift towards higher altitudes, the significance of these existing PAs in the region will become increasingly crucial. However, it is important to acknowledge that these isolated "sky islands" may eventually lose their effectiveness in conservation over time due to their lack of connectivity and isolation. Therefore, we recommend that new conservation strategies must be more engaged with less-considered taxa, such as amphibians, and focus on prioritizing ecologically representative and well-connected systems of PAs that are governed equitably to ensure their long-term success.

5. Conclusion

In this study, we comprehensively assessed the status of *Neurergus* newts considering both climate change and LULCC scenarios. Our approach involved identifying the current and future climatic suitable habitats, analyzing the corresponding LULC patterns in these areas, and evaluating changes at both the broad scale and within a 500-meter buffer around their presence. The findings of this research indicate a concerning decline in LULC suitability within the current and future climatically suitable habitats for *Neurergus* species. It is important to recognize that ecological niche models have inherent limitations in accurately predicting the realized niche of a particular species, as they do not fully account for the complex interactions of biotic and abiotic factors that influence amphibian habitat suitability. Factors such as competition, predation, chemical pollution, and disease can significantly affect the suitability of amphibian habitats (Piha et al., 2007; Hof et al., 2011). Incorporating these intricate variables into predictive models poses significant challenges, particularly given the extensive scope of our study region. While our study did not encompass a comprehensive ecological niche for *Neurergus* species, the examination of the relationships between climate and land-use is valuable for understanding how these factors collectively shape amphibian habitats, which are key determinants of their suitability. Consequently, it is crucial to implement significant measures to mitigate these factors and preserve the viability of these habitats for the *Neurergus* species. Among the backdrop of the worldwide shift in climate patterns, it is imperative to pinpoint priority zones for the preservation and revitalization of biodiversity, especially within mountain ecosystems (Hama and Khwarahm, 2023). The initial implementation of a management and monitoring strategy should function as a mechanism for controlling human activities, encompassing the mitigation of habitat degradation and the mitigation of excessive grazing across identified habitats of the species. Additionally, there should be a central emphasis on the preservation of the species' appropriate habitats. The existing PAs do not serve as crucial reserves for safeguarding

Middle Eastern newts against climate change scenarios. To enhance their conservation efficacy, we recommend to strengthening protection measures in less-restricted PAs and establish strictly regulated reserves in the identified conservation gap areas.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2023.e02739.

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