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# Where will Lycian salamanders, genus *Lyciasalamandra*, be in the near future in southwestern Anatolia, Turkey?

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**Abstract.** Lycian salamanders, genus *Lyciasalamandra*, are a group of seven allopatric, endangered species restricted to the Mediterranean coast of Anatolia, Turkey and certain adjacent Aegean islands. In this study, we created maps to prediction the potential ranges for six of these species using a maximum-entropy algorithm to identify the most significant environmental factors that shape their distribution. These projections were created under current climate conditions and for three future periods (2011–2040, 2041–2070, and 2071–2100), using two shared socioeconomic pathways (SSPs), middle-of-the-road (SSP370) and pessimistic (SSP585). We found that temperature and precipitation are the most important factors influencing the distribution of these salamanders in southwestern Turkey. Under both SSP scenarios, we found that five *Lyciasalamandra* species are likely to shift or reduce their ranges in the near future, while one species (*L. antalyana*) was predicted to expand its range. For the five negatively affected species, whose ranges are already highly ranges, this predicts that climate change combined with high anthropogenic pressure poses a serious risk of extinction. Significant population declines are predicted, particularly for *L. billae* and *L. luschani*. We hope that our findings can serve as a resource for the long-term conservation of these species and aid decision-makers in the development of effective management strategies.

**Key words.** Ecological niche modelling, climate change, Mediterranean, Asia Minor, Turkey

## Introduction

Global climate change is an alarming threat to biodiversity worldwide and is predicted to result in a significant loss of biodiversity in the Mediterranean region (Barnosky et al., 2011). Climate is the main driver affecting the distribution, food sources, and/or breeding ability of species (Root et al., 2003; Brown et al., 2016). Some populations can develop responses against major environmental changes such as climate change or habitat alterations by adapting their long-term behaviour patterns (Dunn and Whinkler, 2010). For instance,

animals can shift their breeding behaviour in response to environmental warming by altering their migration patterns and moving toward colder climates or to higher elevations (Guisan et al., 1995; Pounds and Puschendorf, 2004; Dunn and Whinkler, 2010; Aguirre-Gutierrez et al., 2017), or they may reduce or expand their range as the local climate regime requires (Metzing and Gerlach, 2001). Nevertheless, it is well documented that endemic or restricted-range species are at far greater risk from the threats of environmental change, because they appear to have a fundamentally limited ability to develop adequate long-term responses (Mouillot et al., 2013).

Predicting changes in species' ranges is of increasing interest to conservation scientists so that the loss of key habitats may be prevented (Pereira et al., 2010; Dawson et al., 2011; McMahon et al., 2011). In this context, ecological niche models (ENMs) have been one of the most widely used methods over the past decade (Sillero et al., 2021) when it comes to making decisions about conservation prioritization. ENMs are used to create correlative models of environmental conditions that meet a species' ecological requirements based on data regarding its presence, presence/absence, or abundance at multiple locations (Warren and Seifert, 2011; Ishihama et al., 2019; Sillero et al., 2021). A large number of studies have been done to determine whether climate change causes shifts in species' life cycles and/or notable

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events of species turnover or disappearance. This is because only a few species seem capable of adapting to climate change (Visser et al., 2006; Hitch and Leberg, 2007; Warren and Seifert, 2011; Lowe, 2012).

Amphibians are among the most widespread vertebrates worldwide and currently include more than 8000 known species (AmphibiaWeb, 2022), but 40% of these are threatened with extinction (Bishop et al., 2012). They are among the most vulnerable groups of vertebrates to climate change, mainly due to the ecological requirements needed to preserve permeable skin and shell-less (non-amniotic) eggs, in addition to a complex, water- and moisture-based life cycle (Stuart et al., 2004; López-Alcaide and Macip-Ríos, 2011; Duan et al., 2016). This situation is compounded by the limited dispersal abilities of amphibians, which especially holds true for salamanders (Parra-Olea et al., 2005; Velo-Antón et al., 2013; Sutton et al., 2015; Tok et al., 2016a).

Lycian salamanders, genus *Lyciasalamandra*, are a group of seven allopatric species, including *L. antalyana* (Başoğlu & Baran, 1976), *L. atifi* (Başoğlu, 1967), *L. billae* (Franzen & Klewen, 1987), *L. fazilae* (Başoğlu & Atatür, 1974), *L. flavimembris* (Mutz & Steinfartz, 1995), *L. helverseni* (Pieper, 1963), and *L. luschani* (Steindachner, 1891), that demonstrate an exceptional case of microendemism (Sparreboom, 2014; Veith et al., 2016, 2020). Lycian salamanders are slender, terrestrial, and viviparous salamanders (Sparreboom, 2014). They can be found in restricted areas of relatively small habitat patches and are endemic to a stretch of roughly 385 km along the Mediterranean coast of Turkey, ranging from the Menteşe Mountains in the west to southeastern parts of the western Taurus Mountains in the east, as well as to certain adjacent Greek islands in the Aegean Sea (Veith et al., 2001; Öz et al., 2004; Eleftherakos et al., 2007; Franzen et al., 2008; Sparreboom, 2014; Göçmen and Karış, 2017; Fig. 1). They inhabit north-facing slopes (Franzen et al., 2008; Göçmen et al., 2013) covered with pine forests and Mediterranean maquis vegetation (Veith et al., 2001; Rödder et al., 2011), at elevations from 40–1150 m.

Their natural habitat has characteristically hot and dry summers along with mild and rainy winters. These animals use subterranean refuges, such as deep, humid crevices in karstic limestone, to reduce the impact of adverse weather conditions (Sparreboom, 2014). Within their restricted natural ranges, these salamanders are threatened by habitat loss caused by urbanization, forest fires, and over-collection for scientific purposes. Hence, all species of Lycian salamanders are currently listed in threatened

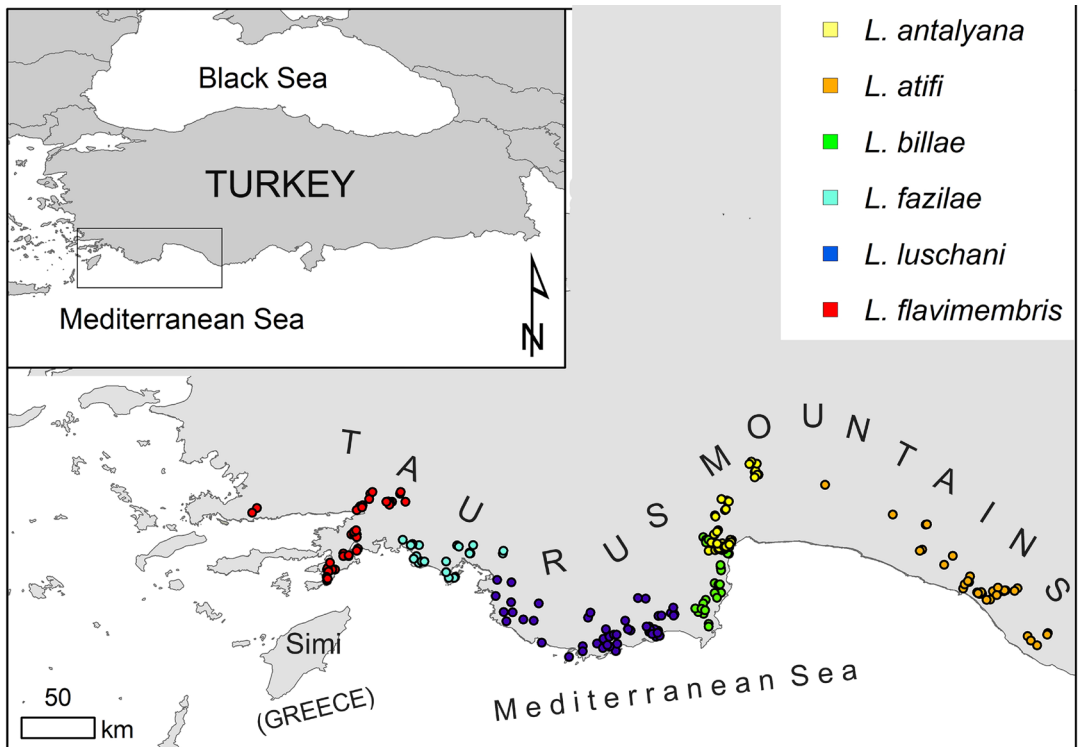
categories of the IUCN Red List: two are considered Vulnerable (*L. luschani*, *L. helverseni*), four Endangered (*L. atifi*, *L. antalyana*, *L. fazilae*, *L. flavimembris*), and one as Critically Endangered (*L. billae*). Predicting the future ranges of these species would help conservationists implement more effective long-term conservation and management strategies.

The purpose of this study is to estimate the present and future distribution of suitable habitats for six of the seven species of Lycian salamanders, to the exclusion of the Greek island endemic *L. helverseni*. To do that, we developed a habitat suitability model using bioclimatic variables encompassing the known ranges of these species in mainland Turkey. We performed a Maximum Entropy analysis to identify key environmental factors with high conservation value in the currently suitable habitats.

## Materials and Methods

**Study area and species occurrence records.** Our study focused on *L. antalyana*, *L. atifi*, *L. billae*, *L. flavimembris*, *L. fazilae*, and *L. luschani*, which occur along a narrow coastal stretch in southwestern Turkey (Fig. 1). The study area has a hot-summer Mediterranean climate (Köppen climate classification: Csa; Beck et al., 2018). The Lycian salamanders' native ranges extend across two provinces (Muğla and Antalya). Air temperature typically varies from 9.9–22.0°C and rarely falls below –12.6°C or rises above 40.6°C in Muğla Province. The average annual precipitation and temperature are 1059.4 mm and 15.4°C, respectively. In Antalya Province, air temperature ranges from 14.1–24.7°C and rarely falls below –4.6°C or rises above 45°C. The average annual precipitation and temperature are 1059.4 mm and 19.0°C, respectively (Turkish Meteorological Stations, 2022).

We gathered 254 occurrence records for the six species from the published literature (Başoğlu and Atatür, 1974; Mutz and Steinfartz, 1995; Veith, 2001; Öz et al., 2004; Johannesen et al., 2006; Beukema et al., 2009; Akman et al., 2011, 2013; Göçmen and Akman, 2012; Göçmen et al., 2011, 2013, 2018; Akman and Godmann, 2014; Oğuz et al., 2014; Şenol, 2015; Üzümlü et al., 2015; Yıldız and Akman, 2015; Dereağzı, 2016; Godmann et al., 2016; Tok et al., 2016b; Göçmen and Karış, 2017; Arslan et al., 2018, 2020; Veith et al., 2016, 2020; Bülbül and Özkan, 2021; Dilbe, 2021). We confirmed about 80% of these records during our previous fieldwork between 2004 and 2021. All records were used to construct the ENM and to predict the effect of climate change on Lycian salamanders. We



**Figure 1.** The mainland ranges of six species of Lycian salamanders, genus *Lyciasalamandra*, in southwestern Anatolia, Turkey (revised from Gülçin et al., 2022). Records are indicated by colour-coded circles.

confirmed the number of records for each species as 62 (*L. antalyana*), 35 (*L. atifi*), 36 (*L. billae*), 46 (*L. flavimembris*), 24 (*L. fazilae*), and 51 (*L. luschani*).

Missing coordinates for localities gathered from the literature were referenced to the closest suitable location (distance < 1 km) using Google Earth Pro v7.1.5. All records were georeferenced using the WGS84 coordinate system and checked with ArcGIS (v10.7, ESRI, California, USA). Using coordinate data from different protocols of fieldwork in different studies could cause an overestimation of the predicted distribution and autocorrelation (Hijmans et al., 2017). To minimize sampling bias and guarantee a homogeneous sampling effort (Merow et al., 2013; Boria et al., 2014; Fourcade et al., 2014; Sillero et al., 2021), we randomly sub-selected one point for each grid cell per 1-km radius buffer around each occurrence record using the *spThin* v0.2.0 (Aiello-Lammens et al., 2015) in R software environment. Therefore, we thinned out the total of 254 records and retained 180 for six *Lyciasalamandra* species, 30 records for *L. antalyana*, 29 for *L. atifi*, 28 for *L. billae*, 25 for *L. flavimembris*, 19 for *L. fazilae*, and 49

for *L. luschani*. We did not include *L. helverseni* in the analyses due to a low number of records for that species and their close proximity to one another (< 5 occurrence points after thinning).

We hypothesized that the study area had been accessible to the six species over statistically relevant periods (Soberón and Peterson, 2005) and presumed that Lycian salamanders could in theory be distributed all across southwestern Anatolia. Accordingly, we masked the environmental variables with a polygon between 35° and 38°N and 26° and 34°E to represent the study area (the theoretically accessible area for the members of the genus; Soberón and Peterson, 2005). In other words, any area where the genus could not feasibly disperse was excluded from the study area (Anderson and Raza, 2010). We also buffered climate variables by 1° representing the dispersal area and drew the border of the distribution area for each species, reflecting the limited dispersal capability of individuals.

**Environmental layers.** We initially used 19 bioclimatic variables as predictors for the present-day distribution. These were obtained from the CHELSA

database (Karger et al. 2017, 2021) at a spatial resolution of 30 arc-seconds (ca. 1 km), which produces these data from monthly temperature and precipitation figures as averages of the period from 1979–2013. CHELSA operates on monthly means and is based on a quasi-mechanistic statistical downscaling of the ERA-interim global circulation model with a GPCC bias correction (Karger et al. 2017). Using a high number of predictor variables in relation to low sample size is one of the major problems with ENM because it might cause model overfitting (Fielding and Bell, 1997). We therefore followed Naimi et al. (2022) and used at least 19 occurrence records and four predictors.

We checked the variance inflation factor (VIF) among all bioclimatic variables to calculate the degree of multicollinearity via the *usdm* package (Naimi, 2015). We set a VIF value of 10 and a correlation threshold of 0.75, as recommended by Guisan et al. (2017). Using a stepwise procedure, we retained only four bioclimatic variables to focus on values that closely reflected the ecological requirements of the species (Veith et al., 2001; Franzen et al., 2008; Sparreboom, 2014). The variables we selected were Temperature Seasonality (BIO4), Max Temperature of Warmest Month (BIO5), Annual Precipitation (BIO12), and Precipitation of Driest Month (BIO14).

The future habitat suitability of Lycian salamanders was estimated by projecting fitted models onto five different global circulation models, including GFDL-ESM 4.1 (Dunne et al., 2020), UKESM1.0-LL (Jones, 2019), MPI-ESM1-2-HR (Müller et al., 2018), IPSL-CM6A-LR (Boucher et al., 2020), and MRI-ESM2.0 (Yukimoto et al., 2019) with two shared socioeconomic pathways (SSPs), middle-of-the-road (SSP370) and pessimistic (SSP585) to represent the levels of uncertainty in climate model projections (Sanderson et al., 2015). Bioclimatic variables at a spatial resolution of ~1 km were obtained from the 6<sup>th</sup> Climate Model Intercomparison Project ([https://www.worldclim.org/data/cmip6/cmip6\\_clim30s.html](https://www.worldclim.org/data/cmip6/cmip6_clim30s.html)) over three 30-year periods (2011–2040, 2041–2070, 2071–2100).

We modelled habitat suitability to estimate potential ranges of Lycian salamanders for the current climate and for the three projected future climate scenarios using Maximum Entropy Modelling (MAXENT v3.4.1; Phillips et al., 2006, 2008, 2017). We implemented the leave-one-out method (Phillips et al., 2006) whereby the number of bins ( $k$ ) is equal to the number of occurrence localities ( $n$ ) in the data set for each species, which is recommended when working with relatively small data sets (Pearson

et al., 2007; Shcheglovitova and Anderson, 2013). We used the R package *ENMeval* v2.0.0 (Muscarella et al., 2014; Kass et al., 2021) to optimize model complexity and balance goodness-of-fit and predictive ability, and to compute maximum entropy models. We built models with regularization multiplier values ranging from 0.5–10 (in increments of 0.5) and with six different feature class combinations (L, LQ, H, LQH, and LQHP, LQHPT), where L = linear, Q = quadratic, H = hinge, P = product, and T = threshold, resulting in 120 individual model runs for each species. Model accuracy was evaluated using four evaluation metrics in *ENMeval* (Muscarella et al., 2014; Kass et al., 2021): (1) the area under the curve (AUC) of the receiver operating characteristic plot for test localities ( $AUC_{TEST}$ ; Hanley and McNeil, 1982; Peterson et al., 2011); (2) the difference between training and testing the AUC ( $AUC_{DIFF}$ ; Warren and Seifert, 2011); (3)  $OR_{10}$  (10% training omission rate) for test localities (Fielding and Bell, 1997; Peterson et al., 2011); and (4) the Akaike Information Criterion corrected for small sample sizes ( $AIC_c$ ; Burnham and Anderson, 2004; Warren and Seifert, 2011). Additionally, we followed the concept of a null model (Raes and ter Steege, 2007) to evaluate the models. Bohl et al. (2019) proposed evaluating models on the same withheld occurrence data as the empirical model. We implemented null ENMs with 100 iterations using the method of Bohl et al. (2019) with the extension of Kass et al. (2020), and we visualized the performance of the empirical model against the null model averages using *ENMeval* (Kass et al., 2021). Each selected model for each species was run with 30 iterations. We applied the 10-percentile training presence logistic threshold approach as recommended by Liu et al. (2005) to transform the complementary log-log regression (cloglog) output into a continuous map of the presence-absence distribution and used it to calculate potential habitat size via the *raster* package in R (Hijmans et al., 2015). The cloglog output represents habitat suitability from 0 (unsuitable) to 1 (suitable). Results were imported and visualized with *rasterVis* (Lamigueiro and Hijmans, 2021) and ArcGIS v10.7.

## Results

We selected the best model for each species based on its statistical performance and low complexity, reduced to four evaluation metrics and null models (Table 1). All selected models had a high average area under the curve for training data (AUC 0.914–0.980). The four environmental factors were determined to impact the

**Table 1.** Parameters and performance statistics of the best models for an assessment of members of the genus *Lyciasalamandra*, using the following column abbreviations: feature class (FC); regularization multiplier (RM); areas under curves for “training” the model ( $AUC_{\text{TRAIN}}$ ), the difference between training and testing ( $AUC_{\text{DIFF}}$ ), and the training dataset value for the null model ( $AUC_{\text{TRAIN-NULL}}$ ); the corrected Akaike Information Criterion ( $AIC_c$ ); the 10% training omission rate ( $OR_{10}$ ); the Z-value (Z); and the p-value (p).

Species	FC	RM	$AUC_{\text{TRAIN}}$	$AUC_{\text{DIFF}}$	$AUC_{\text{TRAIN-NULL}}$	$AIC_c$	$OR_{10}$	Z	p
<i>L. antalyana</i>	LQH	1.0	0.973	0.023	0.669	603.994	0.100	7.328	< 0.000
<i>L. atifi</i>	LQ	0.5	0.978	0.027	0.601	533.627	0.103	9.609	< 0.000
<i>L. billae</i>	LQH	2.5	0.914	0.111	0.605	593.687	0.111	6.013	< 0.000
<i>L. fazilae</i>	H	3.5	0.959	0.040	0.562	359.897	0.111	5.284	< 0.000
<i>L. flavimembris</i>	LQH	2.0	0.980	0.120	0.615	445.981	0.125	6.020	< 0.000
<i>L. luschani</i>	LQH	1.5	0.951	0.041	0.619	982.700	0.104	10.839	< 0.000

distribution of Lycian salamanders to different degrees (Table 2): (1) temperature seasonality (BIO4, 9–67%), (2) maximum temperature of the warmest month (BIO5, < 0.1–19%), (3) annual precipitation (BIO12, 7–58%), and (4) precipitation of driest month (BIO14, 6–44%). The potential distribution of the species *L. antalyana*, *L. atifi*, *L. billae*, and *L. flavimembris* was mainly shaped by precipitation-related variables (BIO12, 14).

The present-day range models generally overlapped the known ranges of the species (Fig. 1). Nearly all species’ ranges were predicted to shrink in both moderate and pessimistic climate scenarios by the year 2100 (Fig. 2, Table 3). The present-day range of *L. antalyana* (Figs. 1, 2) is largely determined by annual precipitation (53%; Table 2). According to future projections, the area with suitable habitats for this species is predicted to increase, especially toward the east. It is the only *Lyciasalamandra* species that may expand its range (Table 3). The present-day range of *L. atifi* is shaped by both annual precipitation and precipitation in the driest months (57% and 33%, respectively). The potential habitat of this species is predicted to shrink by 7–78%. For *L. billae*, key figures

for its present-day range are temperature seasonality (56%) and annual precipitation (37%). In the future, there is a possibility that the habitat supporting this species may completely disappear in the 2071–2100 period. For *L. fazilae*, the key value is temperature seasonality (67%), and its potential habitat is projected to shrink by 14–74%. The present-day range of *L. flavimembris* is shaped by annual precipitation (55%) and precipitation in summer (44%). Soon, its potential range is predicted to expand by 2–5% during the 2011–2040 period, but it may suffer a shrinkage between 33% and 63% in the other projected time periods. The range of *L. luschani* is affected mainly by temperature seasonality (66%). Our projections show that the species’ potential habitat will shrink by 27–90%. According to these models, we estimate that the distribution of the six *Lyciasalamandra* species is mainly shaped by temperature seasonality and annual precipitation. Overall, SSP scenarios emphasize that the suitable habitats for all Lycian salamanders with the exception of *L. antalyana* are predicted to decrease significantly.

## Discussion

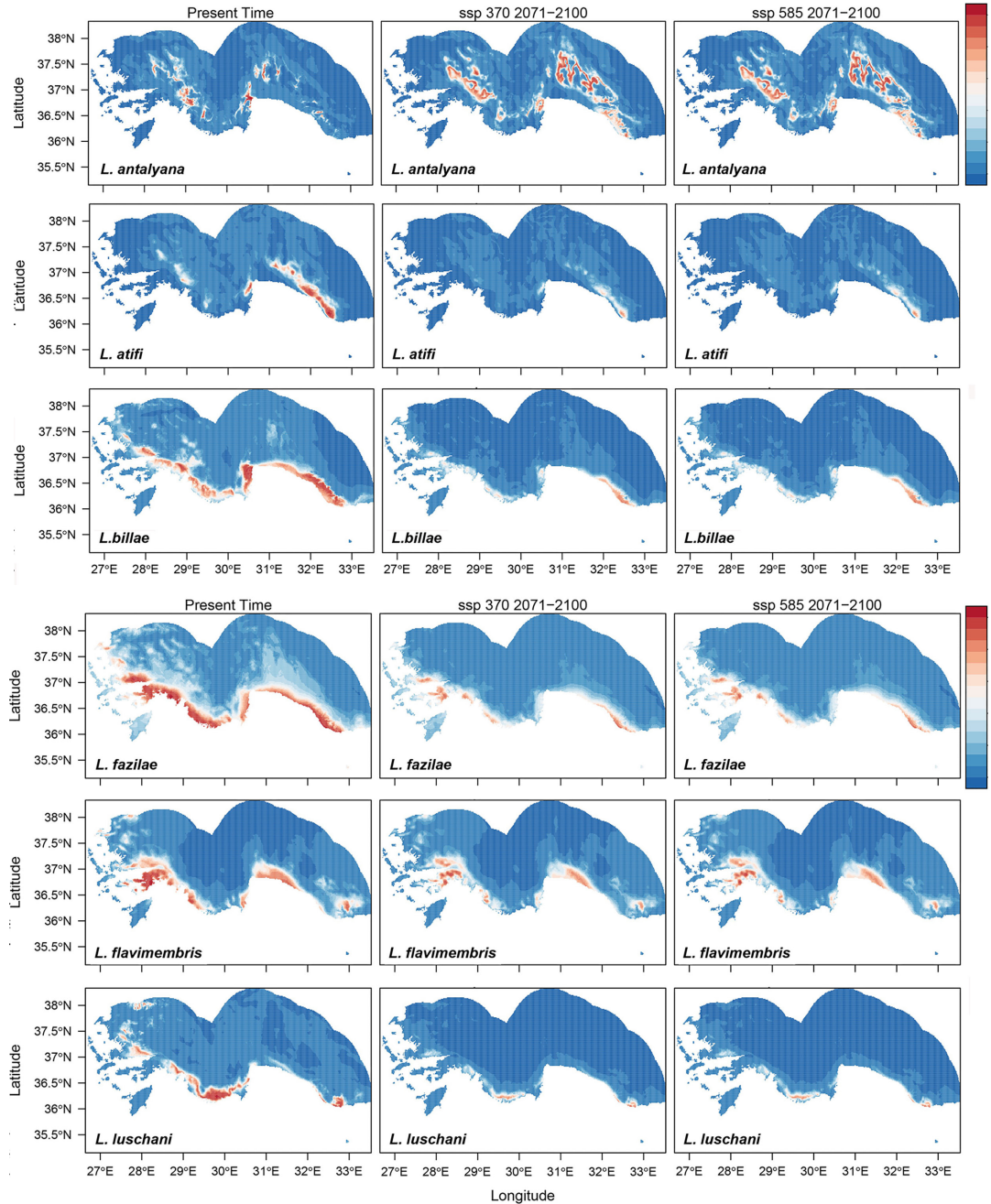
Lycian salamanders mainly occur in the western Taurus Mountains along the Mediterranean coast of Turkey (Veith et al., 2016, 2020). Their diversification started between 12.3 and 10.2 mya, around the final emergence of the mid-Aegean trench (Veith et al., 2016). However, during times of climate change over the history of the Mediterranean region, these salamanders could not spread further due to their limited environmental tolerance and dispersal ability, not even toward the more suitable southern Anatolian environments where modern Lycian salamander species occur (Veith et al.,

**Table 2.** Contributions (%) of the four key bioclimate environmental variables (see the text for abbreviations) that created the best models for the environmental needs of Lycian salamanders, genus *Lyciasalamandra*.

Species	BIO4	BIO5	BIO12	BIO14
<i>L. antalyana</i>	9.31	18.93	53.02	18.74
<i>L. atifi</i>	8.56	1.21	57.51	32.71
<i>L. billae</i>	55.82	0.98	37.00	6.20
<i>L. fazilae</i>	67.36	< 0.00	27.78	4.87
<i>L. flavimembris</i>	0.79	0.09	55.37	43.75
<i>L. luschani</i>	66.13	1.46	6.57	25.83

2016). It should be noted here that the narrow range of these species also poses an important threat by rendering them more sensitive to climate effects. According to the projections of future climate change by 2100, both positive and negative effects can be produced,

which appear set to affect Lycian salamander species differently. Our results indicate that the potential habitats of the majority of species, which are distributed notably close to each other at present, will disappear, and only *L. antalyana* may expand its range. Our dataset shows



**Figure 2.** Climate habitat suitability maps for six Lycian salamander species, genus *Lyciasalamandra*, in southwestern Anatolia, Turkey, predicting their distributions using present-day conditions and projected for the years 2071–2100 using conditions predicted using two shared socioeconomic pathway (SSP) scenarios, SSP370 and SSP585. Probability of presence increases from blue to red.

**Table 3.** The average projected distributional loss or gain (%) for six Lycian salamander species, genus *Lyciasalamandra*, considering future (2011–2040, 2041–2070, 2071–2100) environmental conditions with two shared socioeconomic pathway (SSP) scenarios, SSP370 and SSP585.

Species	SSP 370			SSP 585		
	2011–2040	2041–2070	2071–2100	2011–2040	2041–2070	2071–2100
<i>L. antalyana</i>	50	184	273	51	238	285
<i>L. atifi</i>	-8	-49	-73	-7	-57	-78
<i>L. billae</i>	-35	-82	-100	-37	-92	-100
<i>L. fazilae</i>	-14	-37	-58	-14	-43	-74
<i>L. flavimembris</i>	2	-33	-55	5	-37	-63
<i>L. luschani</i>	-27	-52	-75	-27	-59	-90

that temperature and precipitation are the two key factors influencing the distribution of Lycian salamanders in southwestern Turkey, which is in line with the published literature (Rödger et al., 2011; Arslan et al., 2020; Veith et al., 2020). These variables are also known to act as the foremost factors affecting the mating frequency and mate-finding success in these salamanders during the breeding season (Başoğlu et al., 1994; Sparreboom, 2014; Veith et al., 2016).

Global warming and its effects on biodiversity pose a defining challenge for conservation biologists. Among the organisms of greater concern, amphibians are particularly threatened by the changing climate, and most of the suitable habitats they currently occupy will likely be disrupted or destroyed (e.g., Alford and Richards, 1999; Bishop et al., 2012; AmphibiaWeb, 2022). However, there are yet other threats that loom, such as habitat loss and fragmentation associated with the changes in land use from agricultural activities and tourism. These issues should be addressed by informing local and central government agencies. The five species of *Lyciasalamandra* that currently have highly restricted ranges are at greater risk from climate change and other threats posed by human activities.

One of the effective conservation initiatives that can be proposed for these species entails the assessment of sites with remaining favourable habitats by way of continuous *in situ* monitoring, which can lead to the discovery of new refuge sites. Such a study was conducted in northern Iran for the Critically Endangered Gorgani salamander, *Paradactylodon gorganensis* (Eiselt & Steiner, 1970), by Hosseinian Yousefkhani (2021) and the results revealed that higher pH (ca. 7.0) and dissolved oxygen (about 55%) values produced a negative effect on the species, while its presence was strongly correlated with low mean water temperature (12°C). From this starting point, an action plan for the species could be developed

more effectively. Research showed that temperature and precipitation directly affected the properties of the salamanders' habitats, and the essential abiotic factors that change by extension, such as water quality, played a significant role in the presence and breeding condition of the species (Hosseinian Yousefkhani, 2021).

Approximately 30% of all known Lycian salamander habitats currently lie within protected areas in Turkey, and the populations outside protected sites are under intense threat of habitat destruction and human pressure. Our results emphasize that long-term conservation and management plans should be urgently implemented to ensure the sustainability of the populations of endemic and endangered Lycian salamanders. Furthermore, the salamander populations are impacted by a wide variety of pressures including low prey availability, wildfires, and habitat loss due to urbanization (Başoğlu et al., 1994, Sparreboom, 2014, Veith et al., 2016, Gülçin et al., 2022). In 2021, large forest fires occurred consecutively over a prolonged period well within the range of the six species, leading to habitat loss and fragmentation (Gülçin et al., 2022). According to the preliminary assessments by Gülçin et al. (2022), *L. atifi* is the most vulnerable species to wildfires, followed by *L. flavimembris* and *L. antalyana*. The same study also pointed out that attempts at habitat restoration in burned areas were likely to do even more damage to the salamander populations. The future of these species depends not only on climate conditions but also on the mitigation of human-induced pressures, but these were not included in our models. Consequently, this presents itself as the main limitation of our study. Nevertheless, we recommend that habitat preferences and quality be evaluated for Lycian salamanders in southwestern Turkey to determine both the most consequential abiotic factors that influence species' presence and breeding success and also the anthropogenic threats, such as



urbanization in industrialized regions. This way, a better framework can be provided for conservation biologists regarding the development of effective action plans to secure the future of these salamanders.

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