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Modeling the Impact of Climate Change on the Distribution of the Cilician Water Frog Lineage (*Pelophylax* cf. *bedriagae* 1) in the Çukurova Plain in Southeastern Türkiye and Implications for Its Future Projections

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***Abstract.*—Climate change presents a considerable challenge to biodiversity, with amphibians being particularly susceptible due to their sensitivity to environmental changes. One of these amphibian groups is the Anatolian water frog complex (genus: *Pelophylax*), a distinct, genetically and phylogenetically differentiated cryptic species whose members are morphologically indistinguishable. In this group, the Cilician water frog lineage (*Pelophylax* cf. *bedriagae* 1) is of particular interest as it is only found in the biodiversity-rich Çukurova Plain in southeastern Türkiye; it faces dual threats from historical overharvesting and impending climate change. In this study, we utilized Maximum Entropy (MaxEnt) modeling to map the Cilician lineage's current habitat suitability and distribution, identify key environmental drivers, and project future range shifts under various climate change scenarios. We compiled 167 georeferenced occurrence records and initially assembled 17 environmental predictors (climatic, topographic, and hydrological). Through a rigorous optimization process, including variable selection (varSel and reduceVar functions) and hyperparameter tuning, the model was refined to utilize the seven most influential predictors, substantially improving its predictive accuracy. Permutation and jackknife tests identified temperature seasonality, minimum temperature of the cold quarter, annual precipitation, ruggedness, slope, and distance to lake as the most important variables influencing the frog's distribution. Response curves further elucidated the specific ecological niche characteristics shaped by these factors. Projections for 2050, 2080, and 2100 under low (GCM-245) and high (GCM-585) carbon emission scenarios consistently predict a pronounced northward shift in the suitable habitat of the Cilician water frog lineage. This shift is accompanied by increased habitat fragmentation and a notable decline in suitability within the lineage's current core range, particularly under the high-emission pathway. Whereas the total climatically suitable area may increase in newly favourable northern regions, the lineage's ability to colonize these areas depends on landscape connectivity and dispersal capabilities. This raises concerns about its potential invasiveness in new ecosystems. Our findings emphasize the need for targeted, adaptive conservation strategies that mitigate the impact of climate change and account for human-induced habitat alterations to ensure the long-term persistence of this narrowly distributed water frog lineage.**

Keywords. species distribution modeling, MaxEnt, climate change, water frog, *Pelophylax*, the Cilician lineage, Türkiye

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Introduction

The increasing severity of climate change poses a substantial threat to global biodiversity, with Türkiye being no exception to its impacts. The Çukurova plain in southeastern Türkiye is of particular concern. The Çukurova plain exhibits a Mediterranean climate characterized by hot, dry summers and mild, rainy winters. These climatic variations play a crucial role in shaping the distributions and life cycles of many species (Lionella et al., 2006). Particularly, the Seyhan and Ceyhan River systems, together with adjoining wetlands, are considered as biodiversity hotspots. Moreover, the Taurus Mountains provide vital ecosystem services. The influence of both on the ecological and genetic diversity of species is well-documented, with the shaping of habitats, the facilitation of species dispersal, and the support of interactions critical to biodiversity being the key factors (Akın et al., 2010; Alphan and Yılmaz, 2005; Plötner et al., 2010). However, the shifting climates and risk factors caused by the climate disasters have the potential to cause alarm for this biodiversity. Projections for the period between 2020 and 2050 suggest a temperature increase ranging from 0.5°C to 4.0°C, accompanied by reductions in precipitation, particularly in western and southern Türkiye (Turp et al., 2014). Some estimates suggest that approximately 1103 of these species, including amphibians, are threatened in the region (Ambarlı et al., 2016).

A fundamental understanding of species distributions is paramount for effective conservation strategies, particularly in the face of environmental change. The integration of species distribution models (SDMs) into conservation strategies allows for the prediction of how species may shift their ranges in response to changing climatic conditions and habitat alterations (Ashoori et al., 2018; Blaustein et al., 2010). These models analyse the relationship between species occurrences and environmental variables, thus enabling the identification of potential future habitats and the assessment of vulnerability to extinction (Becker and Zamudio, 2011; Ferrante et al., 2017). Therefore, species distribution modeling (SDM) has emerged as a powerful tool for predicting and understanding spatial patterns (Elith et al., 2010; Warton and Shepherd, 2010). Specifically, maximum entropy (MaxEnt) modeling is advantageous due to its ability to work with presence-only data and its effectiveness in handling incomplete datasets (Kim et al., 2021; Yuan et al., 2015). MaxEnt utilizes an optimization algorithm to estimate the probability distribution of species occurrences based on environmental variables, thereby allowing researchers to predict potential habitats and assess the impacts of environmental changes on species distributions (Buisson et al., 2010; He et al., 2024). The model seeks to find the most uniform distribution that still respects the observed data, thus providing a robust prediction of species distributions (Cao et al., 2022; Fitzpatrick et al., 2013). The methodological rigor contributes to the reliability of conservation planning efforts by providing insights into the potential future distributions of species in response to climate change and habitat alterations (Briceño et al., 2020; Duan et al., 2023). In addition to its predictive capabilities, MaxEnt allows for the incorporation of various environmental variables, such as temperature, precipitation, and land use, which can influence the habitat suitability for distinct species (Ashraf et al., 2017; Ma et al., 2021). Through the analysis of these variables, researchers can identify critical habitats requiring protection and develop targeted conservation strategies that consider the unique ecological requirements of each species (Gagula et al., 2024; Pisarenko and Makunina, 2020).

Amphibians, as bioindicators of ecosystem health, play a crucial role in monitoring environmental changes such as habitat quality and climate. They are notably vulnerable to habitat loss (Deikumah et al., 2014; Nori et al., 2015). One of these potential target amphibian groups is the Anatolian water frog complex (genus: *Pelophylax*), which is comprised of a distinct degree of genetically and phylogenetically differentiated, and morphologically indistinguishable cryptic species. They live in diverse types of freshwater habitats, and their sensitive skin makes them vulnerable to environmental changes such as climatic and geological changes (Akın et al., 2010; Beerli et al., 1996; Plötner et al., 2010). Comprehensive mitochondrial DNA analysis revealed the existence of three main haplogroups (MHG) in Anatolia. MHG6 (referred as *Pelophylax*. cf. *bedriagae* 2) is the widest group and distributes from western Anatolia to the north of the Caspian Sea (Akın et al., 2010; Akın Pekşen, 2015; Plötner et al., 2010). In contrast, MHG4 and MHG5 are exclusively found in the Çukurova or Cilician plain in southeastern Türkiye, where MHG4 (Cilician West) is restricted to regions west of the Amanos Mountains, and MHG5 (Cilician East) is mostly found in areas to the east of the Amanos Mountains. These two groups are genetically older and more differentiated from other populations in Anatolia. In addition, there is a close phylogenetic connection between the Cilician haplogroups and *P. bedriagae* populations in Syria, Lebanon and Jordan (Akın et al., 2010; Akın Pekşen, 2015; 2025; Plötner et al., 2010). The nuclear markers (SAI-1+RanaCR1 and uqcrfs1) support the hypothesis of evolutionary independence and unique genetic diversity of this group as a single Cilician group, rather than two groups, referred to as the Cilician water frog lineage or *P.* cf. *bedriagae* 1 in this study.

However, these endemic water frog populations belonging to the Cilician water frog lineage (*P.* cf. *bedriagae* 1) in the Çukurova plain (also named Cilician) are under two important threats. First, Cilician populations, especially those from the Ceyhan and Seyhan Deltas in Adana province have been collected for a period exceeding four decades (Akın and Bilgin, 2010; Çiçek et al., 2021; Kürüm, 2015). The modeling estimate of these harvested populations based on mark and recapture analysis indicated a population decline of approximately 20% per year. If this high rate of overharvesting persists, the populations will encounter a 90% risk of extinction within 50 years (Çiçek et al., 2021). Secondly, the Cilician lineage is found in the Çukurova plain of Türkiye, where drier and hotter summers are expected in 2030, 2050, and at the end of the century (Fujihara et al., 2008). Previously, MaxEnt modeling of the endemic *P. caralitanus* lineage belonging to the large MHG6 (referred as *Pelophylax.* cf. *bedriagae* 2) reveals reduction in the potential habitats in southwestern Anatolia and complete disappearance of suitable habitats in the Lake District region (Kıraç et al., 2022). It is evident that they face a risk of dramatic climatic changes. Therefore, frogs are a vital model organism for studying the consequences of climate change on amphibian distributions.

The objective of the present study is to map the current habitat suitability and distribution of the Cilician water frog lineage (*P.* cf. *bedriagae* 1) across its range and to identify the key environmental variables influencing its distribution. Utilizing advanced MaxEnt modeling with customized, optimized settings, in this research, we further aim to predict the future habitat suitability and potential range shifts of the Cilician water frog lineage under different climate change scenarios, specifically the low carbon emission (GCM-245) and high carbon emission (GCM-585) pathways for the years 2050, 2080, and 2100. This comprehensive analysis provides a scientific basis for developing targeted conservation strategies to protect this valuable amphibian group and its associated ecosystems.

Materials And Methods

Study Area and Buffered Study Area

The Adana Plain, which encompasses Çukurova in its southern part and Yukarıova, also known as Anavarza, in the north, is an area where the Cilician water frog lineage (*P.* cf. *bedriagae* 1) is predominantly found. The region is located between latitudes 35° and 38° North and longitudes 34° and 36° East (Figures 1A and B). A Mediterranean climate characterises the Çukurova plain, but orographic effects modify the rainfall patterns, with the tall Taurus Mountains acting as a trap for moisture-rich winds, resulting in higher rainfall in the upland and northern regions of the plain. Conversely, lowland areas are distinguished by hot, humid summers with sparse or absent rainfall. Such natural climatic shifts lead to a cycle of dry and wet periods, resulting in a wide variety of microclimates (Alphan and Yılmaz, 2020; Koç and Paksoy; 2025). The region is characterised by the presence of two primary river systems: the Seyhan and Ceyhan rivers. The Seyhan River originates in the Taurus Mountains and ultimately flows into the Mediterranean Sea (Fujihara et al., 2008). Similarly, the Ceyhan River, which originates in Kahramanmaraş Province and is adjacent to the Seyhan River, also flows into the Mediterranean (Tanrıverdi et al., 2009). The presence of these extensive river systems, alongside

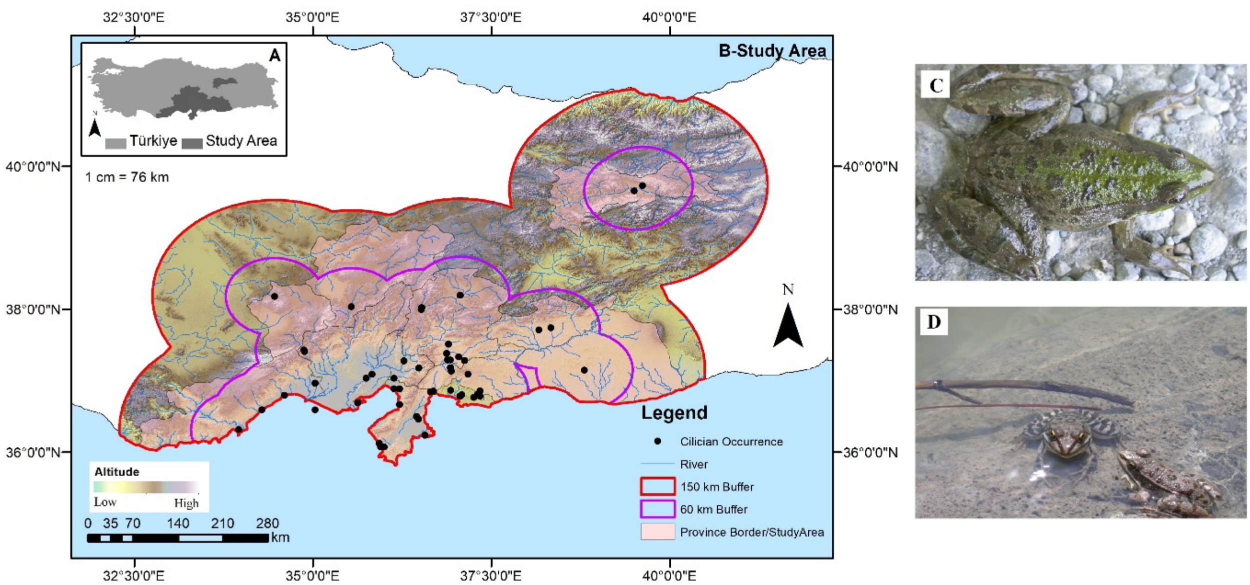

Fig. 1. The Geographic extent of the Cilician water frog lineage (*P.* cf. *bedriagae* 1) occurrence records and the associated buffered study areas. **(A)** The inset map shows the location of the study area within Türkiye. **(B)** The main map displays the study area, with black dots representing individual occurrence points. The purple polygons delineate the 60 km buffer zones around occurrence records, which served as the model calibration area. The red polygon outlines the 150 km buffer area, which represents the larger region onto which the optimized model was projected. The map further illustrates the altitude gradient (from low to high) and major rivers within the study area, which encompasses the provinces of Mersin, Adana, Hatay, Niğde, Kayseri, Kahramanmaraş, Kilis, Gaziantep, Şanlıurfa, Erzincan, Osmaniye, and Adıyaman**. (C)** Cilician Water Frog Dorsal View and **(D)** Cilician Water Frog Habitat View.

their wetlands, marshes, natural lakes, and artificial reservoirs, further enhances the complexity of the habitat. This provides essential breeding grounds and refuge areas for water frog populations (Akın et al., 2010; Dubey et al., 2014). The interplay of these varied aquatic environments fosters robust populations of *Pelophylax* frogs, highlighting both the ecological richness and the importance of conservation efforts in preserving these habitats amidst pressures from climate change and anthropogenic activities (Baláž et al., 2014).

Buffer zones/areas play a crucial role in species distribution modeling by defining the area for model calibration and projection. The selection of buffer distances is typically guided by a species' dispersal capacities and its tolerance of varying environmental conditions (Zhang et al., 2024). In this study, two distinct buffer zones were employed: a 60-km buffer and a 150-km buffer (Figure 1B). The 60-km buffer zone was created around the species' occurrence records and served as the calibration area for the model optimization. This distance was chosen to encompass the immediate environmental context relevant to the known presence points (Figure 1B). Subsequently, the 150-km buffer area defined the broader region onto which the optimized model was projected to predict potential habitat suitability (Figure 1B). These buffer distances were carefully selected to account for the Cilician water frog lineage's potential dispersal abilities and to capture the influence of broader regional environmental gradients. This methodology created a projected study area that extends north from southern Anatolia, primarily along major river systems.

Occurrence Records

For the Cilician water frog lineage (*P. cf. bedriagae* 1), presence-only occurrence data were compiled from existing genetic research. The analysis incorporated a comprehensive dataset comprising 167 georeferenced presence records, encompassing the entire Çukurova plain and neighbouring areas (Figure 1B). The initial recording of these precise latitude and longitude coordinates was conducted using GPS technology. The data points represent individuals identified as belonging to the Cilician water frog lineage through mitochondrial DNA (mtDNA) analysis based on previous studies (Akın et al. 2010; Akın Pekşen, 2015; Akın Pekşen and Plötner, 2025; Plötner et al. 2001; 2010; 2012; 2015). The genetic identification of the lineage was critical to guarantee that the occurrence data precisely represented the target lineage's distribution. The strong phylogenetic signal and substantial sequence length of these genes provided sufficient resolution to define the evolutionary boundaries of the lineage (Ballard and Pichaud, 2013; Zardoya and Meyer, 1996). The spatial distribution of these occurrence records across the designated study area, as Figure 1B illustrates.

Environmental Predictor Data

We assembled a dataset comprising 17 environmental predictors to model the current and future habitat suitability of the Cilician water frog lineage (*P.* cf. *bedriagae* 1) (Table 1). The selection of predictors, including climate, topography, and hydrological availability, was particularly designed to reflect a comprehensive array of factors that are of paramount importance to the ecology of amphibians. We prioritized climatic variables due to their direct impact on the physiological processes of amphibians, their breeding cycles, and their overall survival (Miller et al., 2018; Ray et al., 2016). Fluctuations in temperature and precipitation can exert a substantial influence on breeding success and survival rates (Ray et al., 2016). For this study, nine bioclimatic variables, derived from monthly temperature and precipitation data, were sourced from the WorldClim database version 1.4 (available at https://www.worldclim.org/). All climatic data were obtained at a 30-arc-second resolution. The current conditions were represented by bioclimatic variables from the baseline period of WorldClim 1.4. For future climate projections, corresponding bioclimatic variables were derived from the WorldClim 1.4 dataset, which explicitly processes outputs from the Coupled Model Intercomparison Project, Phase 6 (CMIP6) ACCESS-CM2 model (Eyring et al., 2016). The incorporation of future projections for the years 2050, 2080, and 2100 was conducted under low-carbon (SSP2-4.5) and high-carbon (SSP5-8.5) emission scenarios, with the objective of assessing the impacts of climate change on the distribution of the target lineage.

Topographic variables have been demonstrated to exert a substantial influence on the development of local microclimates, the modulation of water availability, and the shaping of species dispersal patterns (Latimer and Zuckerberg, 2016; Zellweger et al., 2019). Topographic variables were derived from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Models (SRTM DEM) with a 30-m resolution (Nikolakopoulos, 2006), providing altitude data and derived metrics. The variables considered in this study included ruggedness (calculated as the standard deviation of altitude within a neighbourhood), slope (the gradient of the terrain), north aspect, and east aspect (the direction of slopes) (Table 1). The obligate aquatic nature of water frogs is related to hydrological variables. The proximity of these species to permanent water bodies has been identified as a key factor influencing their distribution (Korzikov and Aleksanov, 2018; Nesi et al., 2023). Therefore, distances to lakes, rivers, and wetlands were calculated as Euclidean distances from their respective features (Table 1). The geographical data for these water bodies was obtained from the General Directorate of Water Management of the Ministry of Agriculture and Forestry of the Republic of Türkiye.

Initially, environmental predictors were generated

Table 1: Environmental Predictors Used in Habitat Suitability Modeling for the Cilician Water Frog (*P.* cf. *bedriagae* 1).

Variable Category	Variable Name	Abbreviation	Description	Unit	Included in Optimized Model	Source
Climatic	Annual Precipitation	BIO12	Total annual precipitation.	mm	Yes	WorldClim v1.4 (Current & CMIP6 ACCESS-CM2 for future)
	Mean Diurnal Range	BIO2	Average of monthly (max temp - min temp).	°C	No	
	Isothermality	BIO3	Measures the day-to-night temperature oscillation relative to the annual temperature oscillation.	Ratio	Yes	
	Mean Temperature of Coldest Quarter	BIO11	Average temperature of the coldest three-month period of the year.	°C	Yes	
	Mean Temperature of Driest Quarter	BIO9	Average temperature of the driest three-month period of the year.	°C	No	
	Mean Temperature of Wettest Quarter	BIO10	Average temperature of the wettest three-month period of the year.	°C	No	
	Precipitation of Coldest Quarter	BIO19	Total precipitation during the coldest three-month period of the year.	mm	No	
	Precipitation Seasonality	BIO15	Coefficient of variation of monthly precipitation.	Unitless	No	
	Temperature Seasonality	BIO4	Standard deviation of monthly temperature means (multiplied by 100).	°C * 100	Yes	
Topographic	Altitude	SRTM DEM	Elevation above sea level.	m	No	SRTM Digital Elevation Models (30-m resolution)
	Ruggedness		Standard deviation of altitude within a defined neighbourhood.	Unitless	Yes	Derived from SRTM DEM (30-m resolution)
	Slope		Steepness or gradient of the terrain.	Degrees	Yes	
	North Aspect		Direction of the slope (northness).	Unitless	No	
	East Aspect		Direction of the slope (eastness).	Unitless	No	
Hydrological	Distance to Lakes		The Euclidean distance to the nearest lake.	km	Yes	General Directorate of Water Management, Ministry of Agriculture and Forestry of the Republic of Türkiye
	Distance to Rivers		Euclidean distance to the nearest river.	km	No	
	Distance to Wetlands		Euclidean distance to the nearest wetland.	km	No	

as digital raster layers. Subsequently, all spatial layers were standardized to the Geographic Coordinate System (GCS) WGS 1984 (EPSG:4326) and resampled to a 30-m resolution using nearest-neighbour interpolation. Preliminary data processing and geospatial analysis were conducted using ArcGIS Desktop (version 10.0, Environmental Systems Research Institute, 2010). Subsequently, the prepared environmental data, in conjunction with the Cilician lineage occurrence records, were transferred to the R statistical environment (version 4.0.3, R Core Team, 2020) for subsequent modeling using the raster (Hijmans, 2025) and rgdal (Bivand et al., 2023) packages. A detailed list of environmental predictors is provided in Table 1.

Model Tuning and Assessment

Maximum Entropy (MaxEnt), a machine learning algorithm for species distribution modeling (SDM), was utilized to model the distribution of the Cilician water frog lineage (*P.* cf. *bedriagae* 1). The MaxEnt model estimates habitat suitability based on occurrence records and various environmental predictors (Merow et al., 2013; Muscarella et al., 2014; Nazeri et al., 2012; Phillips et al., 2004, 2006; Young et al., 2009). The complexity of the model in SDM can result in overfitting or underfitting, which necessitates rigorous optimization (Merow et al., 2014; Warren & Seifert, 2011; Vignali et al., 2020). The SDMtune package (Vignali et al., 2020) has been developed to streamline this process, enhancing parameter tuning and model assessment efficiency. Optimization packages have been enhanced the reliability of predictions through systematic evaluation of multiple configurations, a process which is of particular significance in the context of conservation (Ahmadi et al., 2023; Bowen and Stevens, 2020; Freeman et al., 2019; Holder et al., 2020). A seven-step optimization workflow was established, including data collation, initial model, predictor selection, hyperparameter tuning, model complexity assessment, final model fitting, and evaluation. The creation of an SWD object was undertaken to encapsulate species occurrence, environmental data, and background points. The dataset was divided into training (60%), validation (20%), and testing (20%) subsets for evaluation (Hastie et al., 2009; Merow et al., 2014; Vignali et al., 2020). An initial MaxEnt model was fitted using all 17 environmental predictors with default hyperparameters, and performance was evaluated using the area under the curve (AUC) of the receiver operating characteristic

(ROC) curve. A predictor selection process was implemented using the varSel function of SDMtune, which applied an iterative leave-one-out Jackknife approach to identify and remove low-contributing predictors exhibiting high correlations with others. This process was continued until all remaining predictors showed below-threshold correlations (Spearman's rho > 0.80). A new MaxEnt model was retrained with the reduced predictors to minimize multicollinearity and boost performance, assessed with validation data to avoid overfitting.

Hyperparameter tuning was facilitated by the optimizeModel function within SDMtune, employing a genetic algorithm to find optimal settings. The search space included a regularization coefficient range from 0.2 to 5, iteration numbers from 500 to 9900, and combinations of linear, quadratic, product, hinge, and threshold feature classes. The initial population consisted of 20 models that were randomly generated. The model's fitness was evaluated through the AUC, based on validation data. The next generation incorporated the top 40% of the performing models and 20% of the least successful ones, to circumvent premature convergence. This was achieved by employing genetic operators to generate new models through crossover and mutation. A model complexity reduction step improved generalizability and mitigated overfitting via the reduceVar function, identifying predictors with negligible importance. Predictors with non-significant permutation importance were targeted for removal, as assessed through a leave-one-out jackknife test. The validation dataset was then integrated with the training dataset to expand the sample size; the final MaxEnt model was developed using the combined dataset and optimized parameters. The performance of the final model was then evaluated via an independent test dataset.

Habitat suitability across the study area was predicted with the predict function. Two primary spatial outputs were generated for both current conditions and future projections (for the years 2050, 2080, and 2100 under low-carbon (SSP2-4.5) and high-carbon (SSP5-8.5) emission scenarios). The Continuous Habitat Suitability Map represents the initial continuous prediction directly generated by the optimized MaxEnt model, providing a gradient of values (typically 0-1), which quantitatively indicates the environmental suitability for the Cilician water frog lineage across the entire study area. The Binary Habitat Suitability Map, otherwise referred to as the Potential Habitat Map, is a visual representation of the suitability of a particular environment for a given species. To provide a clear, interpretable representation of suitable habitat, the continuous suitability map was transformed into a binary (suitable/unsuitable) map. This conversion was achieved by applying the Maximum Training Sensitivity plus Specificity (MSS) threshold to the continuous suitability values (Guillera et al., 2015; Newbold, 2009; Pineda and Lobo, 2008). The MSS threshold was chosen for its ability to maximize the model's capacity to identify both true positive and true negative rates correctly (Pearson et al., 2004; Pineda and Lobo 2008), thereby enabling precise estimation of potential distribution areas and avoiding overestimation of suitable habitats (Liu et al., 2013).

The additional outputs included the calculation of predictor importance through the implementation of permutation and jackknife tests, in addition to the generation of response curves for predictors that demonstrated critical importance value. We employed permutation importance to assess the contribution of each predictor by measuring the performance decrease upon value shuffling. In contrast, we used jackknife tests to gauge importance by iteratively excluding predictors and tracking changes in AUC. The response curves for the predictors with critical importance illustrated the relationship between environmental variables and predicted habitat suitability, offering insights into species-environment interactions.

Results

Optimized Model Outputs and Performance Metrics

To improve the accuracy of predictions for the Cilician water frog lineage, we modified the standard hyperparameter settings through an optimization process employing machine learning techniques. Through this process, we aimed to develop a final predictive model by adjusting specific factors in the MaxEnt approach. Initially, from a total of 167 occurrence records, 100 were allocated for model training, 33 for validation, and 34 for testing (Figure 1B). The initial model was fitted using all 17 environmental predictors (Table 1). To address both multicollinearity and remove redundant variables, we used the varSel and reduceVar functions sequentially. This process systematically eliminated variables that contributed least to model performance, resulting in the removal of 10 predictors (Table 1). Following this variable selection step, we developed the final model using the remaining seven environmental predictors. This optimization led to a substantial improvement in model performance. The initial model, using all 17 predictors, had an area under the curve (AUC) training value of 0.701 and a test value of 0.637. The refined model, after variable selection, demonstrated a significant increase, with the training AUC value rising to 0.965 and the test AUC value increasing to 0.881.

Key Environmental Variables and Their Influence on Target Lineage Distribution

The key results from the optimized Maxent model reveal the environmental factors that significantly influence the distribution of the Cilician water frog lineage. To identify the relative importance of these factors, both permutation and jackknife tests were performed. The results of the permutation test revealed that the temperature seasonality exhibited the highest importance value of 32.9 (SD ± 0.008). In addition, the minimum temperature of the cold quarter also showed a significant importance value of 21.7 (SD ± 0.006). The annual precipitation exhibited a permutation importance value of 19.4 (SD ± 0.014). Other variables also exhibited stable contributions: slope (value 10.3, SD ± 0.005); ruggedness (value 9.8, SD ± 0.004); and distance to lake (value 5.2, SD ± 0.001). The isothermality showed the lowest permutation importance value of 0.7 (SD ± 0.002) (Table 2).

For additional evaluation of the unique contribution and influence of each environmental predictor on the model's performance, we performed a jackknife test on both the test and training AUCs (Figures 2A-2B). This analysis assesses the gain in AUC when a single variable is used in isolation ("With only" - peach bars) versus the decrease in AUC when a single variable is removed from the model ("Without" - cyan bars). The red-dashed line in the figure shows the AUC of the model incorporating all variables. The jackknife test strongly corroborated the permutation results; the minimum temperature of the cold quarter and temperature seasonality exhibited the highest individual predictive power (largest "With only" bars) and caused the most significant drop in AUC when omitted, thus confirming them as the most influential drivers of the lineage's distribution. Ruggedness was also confirmed as a substantial predictor in both tests. The consistent pattern of predictor importance across Test and Train AUCs indicates the model's robust ability to capture the target lineage's true environmental signal.

Finally, the Response Curves (Figures 3A–3G) were generated to illustrate the relationship between the predicted probability of presence for the Cilician water frog lineage and each environmental variable, with all other variables held at their average values. The analysis showed that for isothermality, the Cilician water frog lineage is unlikely to be found in areas of low isothermality, with suitability increasing sharply at values around 25 and remaining high for values between 30 and 40 (Figure 3A). Regarding the distance to a lake, the probability of presence is highest at short distances (close to 0 km), decreases significantly at approximately 0.5 km, and then remains low as the distance increases (Figure 3B). The lineage demonstrates a high probability of presence in areas with low ruggedness (values near 0). However, it shows a substantial decline in suitability as

Table 2: Relative importance of environmental predictors for the Cilician water frog lineage as determined by permutation importance and percent contribution in the optimized Maxent model.

Variable	Permutation Importance (%)	Std deviation	Percent contribution (%)
Temp Sea.	32.9	0.008	20.5
Min. Tmp. Cold Quarter	21.7	0.006	25
Annual Prep.	19.4	0.014	4
Slope	10.3	0.005	12.5
Ruggedness	9.8	0.004	23.5
Distance to Lake	5.2	0.001	10
Isothermality	0.7	0.002	2.5

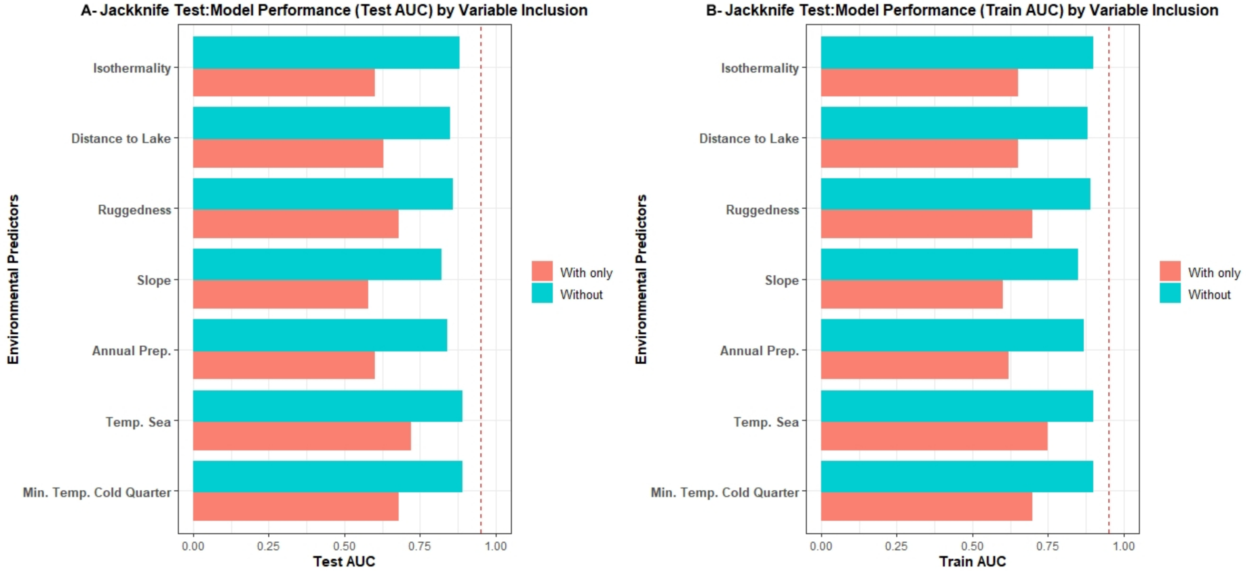

Fig. 2. Jackknife test results for both Test AUC **(A)** and Train AUC **(B)** models. Test AUC **(A)**: shows the accuracy performance of the model on the test data. Using variables alone (peach) and running without them (cyan) are compared. Train AUC **(B)**: Shows the model's performance on the training data.

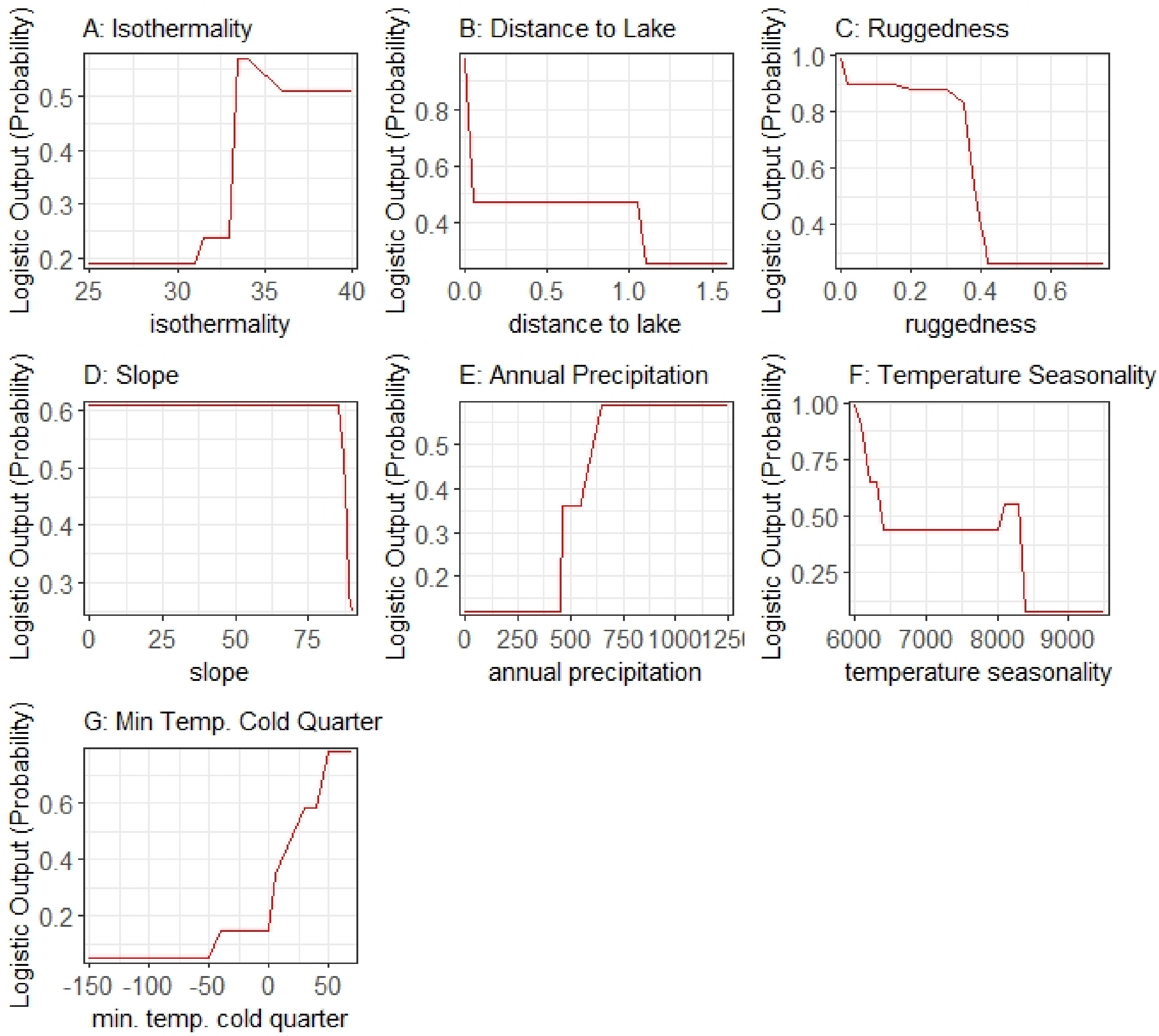

Fig. 3. Response curves showing the key environmental predictors for the Cilician lineage. The X-axis represents the lineage' response to changes in these variables, while the Y-axis displays the logistic probabilities of the lineage. Isothermality **(A)**, distance to lakes **(B)**, ruggedness **(C)**, slope **(D)**, annual precipitation **(E)**, temperature seasonality **(F)**, minimum temperature cold quarter **(G).**

the terrain becomes more rugged, with the probability dropping sharply for ruggedness values greater than 0.2 (Figure 3C). For slope, the probability of presence remains consistently high across the entire range of values analysed (0–75), indicating that it is not a limiting factor (Figure 3D). Annual precipitation also plays a crucial role, with the probability of presence being minimal in areas below 500 mm, but increasing sharply beginning around 500 mm and peaking at higher precipitation levels (above 750 mm) (Figure 3E). For temperature seasonality, the probability of occurrence is highest at lower values, declining substantially around a seasonality of 7000–8000 before a modest increase that stabilizes at a moderate probability for exceedingly high seasonality values (Figure 3F). Lastly, for the minimum temperature of the cold quarter, the probability is low at extremely cold temperatures (below −50°C), increasing steadily as the temperature rises, and reaching its maximum at temperatures above 0°C (Figure 3G).

Predicted Habitat Suitability and Current Distribution

We used the MaxEnt model to create habitat maps for the Cilician water frog lineage. The maps presented herein illustrate the potential habitat of the water frogs within the designated study area (Figures 4A-4N). To make these maps, we applied the Minimum Training Presence (MTP or MSS) threshold to the predicted probabilities. This process turned the suitability scores into simple "suitable" or "unsuitable" categories for the habitat.

Predicted Current Habitat Suitability (Figure 4A) displays a continuous gradient of environmental suitability across the landscape, with warmer colours (e.g., orange, yellow, light blue) indicating higher predicted probabilities of the Cilician water frog's presence. This map shows that a substantial expanse within the south-central region of Türkiye exhibits optimal conditions for the proliferation of the lineage. This matches the known

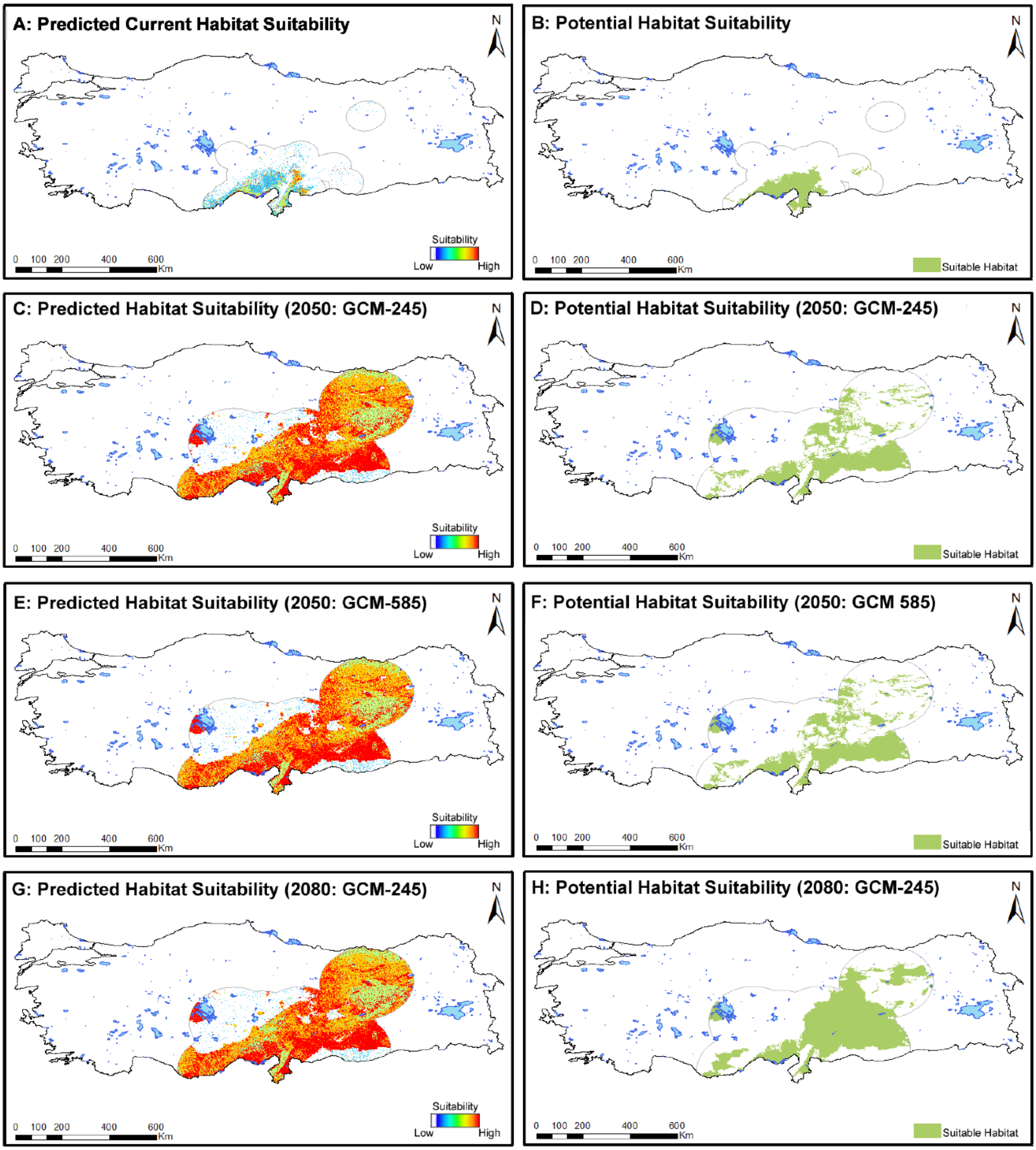

Fig. 4. MaxEnt Predicted Habitat Suitability and Potential Distribution Maps for the Cilician Water Frog Lineage (*Pelophylax* cf. *bedriagae* 1) in Türkiye under Current and Future Climate Scenarios. The maps are arranged sequentially by time step (Current, 2050, 2080, 2100) and scenario (GCM-245, GCM-585). Predicted Suitability maps display a continuous gradient (from low to high suitability). Potential Habitat maps are binary (suitable/unsuitable), derived using the Minimum Training Presence (MTP) threshold. **Panel descriptions: A:** Predicted Suitability (Current Baseline); **B:** Potential Habitat (Current Baseline); **C:** Predicted Suitability (2050; GCM-245); **D:** Potential Habitat (2050; GCM-245); **E:** Predicted Suitability (2050; GCM-585); **F:** Potential Habitat (2050; GCM-585); **G:** Predicted Suitability (2080; GCM-245); **H:** Potential Habitat (2080; GCM-245); **I:** Predicted Suitability (2080; GCM-585); **J:** Potential Habitat (2080; GCM-585); **K:** Predicted Suitability (2100; GCM-245); **L:** Potential Habitat (2100; GCM-245); **M:** Predicted Suitability (2100; GCM-585); **N:** Potential Habitat (2100; GCM-585).

geographic range of the Cilician lineage. There are also smaller areas exhibiting moderate suitability in other parts of the country, indicating the potential for less ideal habitats.

The application of the MSS threshold (specifically, the Minimum Training Presence threshold) to these predicted probabilities resulted in the Predicted Potential Habitat (Figure 4B). The delineation of areas identified as currently suitable habitat (shown in green) is apparent in this binary map. The majority of the suitable habitat

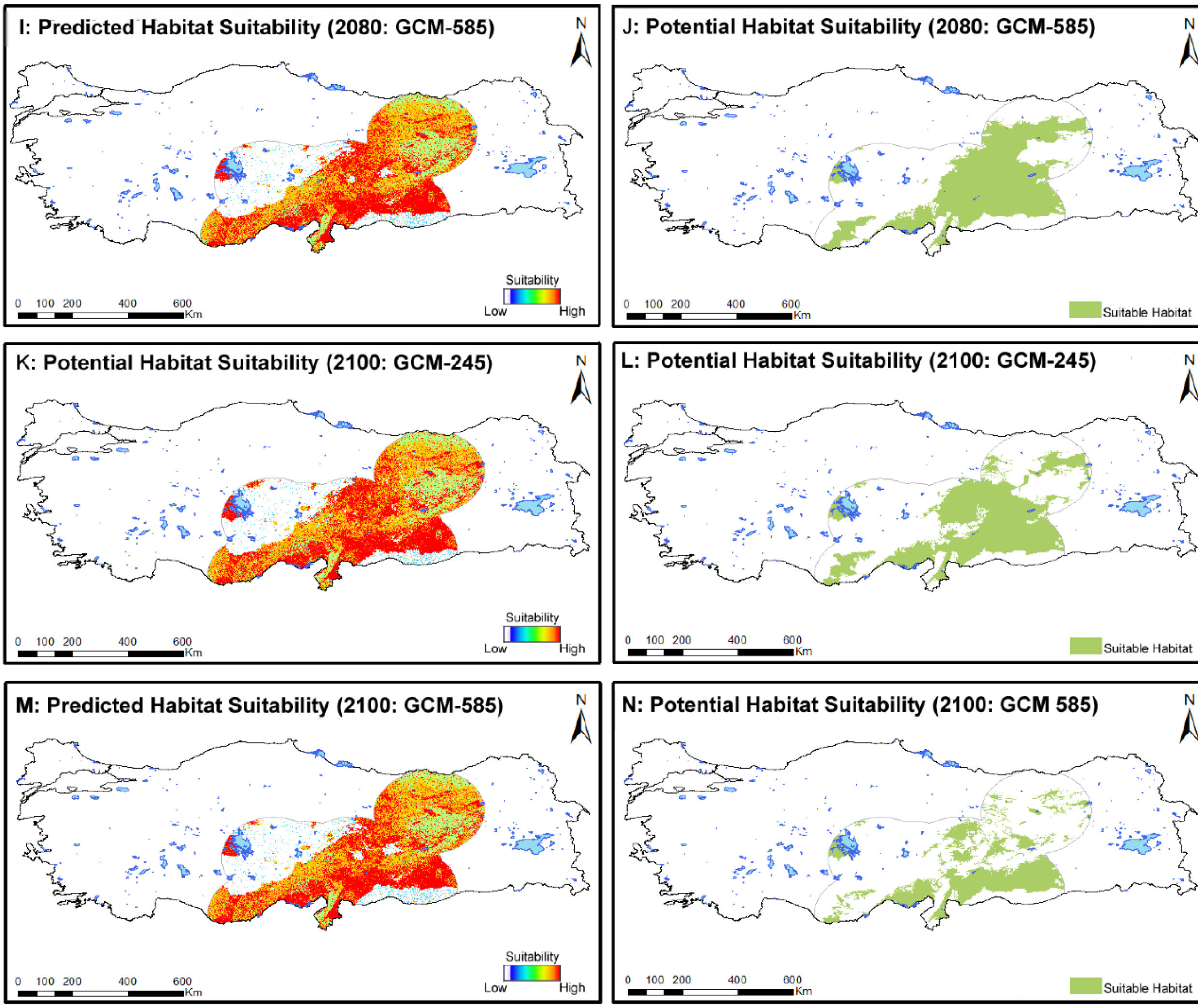

Fig. 4. (Continued). MaxEnt Predicted Habitat Suitability and Potential Distribution Maps for the Cilician Water Frog Lineage (*Pelophylax* cf. *bedriagae* 1) in Türkiye under Current and Future Climate Scenarios. The maps are arranged sequentially by time step (Current, 2050, 2080, 2100) and scenario (GCM-245, GCM-585). Predicted Suitability maps display a continuous gradient (from low to high suitability). Potential Habitat maps are binary (suitable/unsuitable) derived using the Minimum Training Presence (MTP) threshold. **Panel descriptions (Continued): G:** Predicted Suitability (2080; GCM-245); **H:** Potential Habitat (2080; GCM-245); **I:** Predicted Suitability (2080; GCM-585); **J:** Potential Habitat (2080; GCM-585); **K:** Predicted Suitability (2100; GCM-245); **L:** Potential Habitat (2100; GCM-245); **M:** Predicted Suitability (2100; GCM-585); **N:** Potential Habitat (2100; GCM-585).

is concentrated in the southern region, particularly in the Cilician sub-region, extending outwards from the core high suitability areas observed in Figure 4B. This indicates that a sizeable portion of the continuous suitable areas fall above the defined threshold, thereby classifying them as ecologically viable for the lineage according to the model's parameters.

Projected Future Habitat Suitability and Distribution under Climate Change Scenarios

To assess climate change impact on the Cilician water frog's habitat, the optimised MaxEnt model was projected onto future climate scenarios from CMIP6: GCM-245 (low carbon) and GCM-585 (high carbon), for 2050, 2080, and 2100. Predicted and potential habitats were generated for each scenario and time step.

By 2050, the disparities between the low and high emission scenarios become more pronounced, showing a clearer impact of climate change on the lineage's habitat, with the northward shift becoming increasingly evident (Figures 4C-4F). About Predicted Habitat Suitability (Figure 4C), in GCM-245, suitable areas are generally stable, though there may be subtle shifts or reductions compared to the current map, with increased northward expansion. Under GCM-585, there is a marked decrease in the area of highest suitability and a decline in overall suitability in parts of the historical range (Figure 4E). There is also a northward migration of the remaining suitable patches. Concerning the Predicted Potential Habitat (Figure 4D), the GCM-245 habitat is relatively stable, with the potential range being maintained, but expansion into northern areas is projected. However, for GCM-585, suitable habitat is significantly diminished and more fragmented, indicating a substantial loss of suitable areas for the Cilician water frog lineage, with remaining suitable areas concentrated further north (Figure 4F).

Projections for 2080 show a critical situation for the Cilician water frog lineage, with a decline in suitable habitat, particularly under high emission scenarios, and a northward shift of remaining areas (Figures 4G-4J). About Predicted Habitat Suitability, under GCM-245, while some regions of high suitability remain, their extent is reduced in comparison to earlier timeframes, and these regions are progressively situated in more northerly latitudes (Figure 4G). Under GCM-585, a substantial decline in high suitability areas has been observed, with a considerable proportion of the previously suitable habitat becoming moderately or marginally suitable, and any remaining high suitability being concentrated in the extreme north (Figure 4I). Concerning Predicted Potential Habitat, under GCM-245, suitable habitat continues to contract, showing further fragmentation, with the majority of the remaining suitable areas now located in the northern half of Türkiye (Figure 4H). For GCM-585, the projected suitable habitat is severely restricted, appearing as highly fragmented and significantly smaller patches, almost exclusively in the northern part of the country, indicating severe habitat loss and a near-complete northward displacement (Figure 4J).

By 2100, the model projects a severe impact on the Cilician water frog's habitat, especially under the high emission scenario (Figures 4K-4N). Its range will be confined to newly suitable northern areas or drastically reduced elsewhere. With regard to Predicted Habitat Suitability, under GCM-245, the remaining areas of high suitability are minimal and highly fragmented, with a shift towards the northern parts of Türkiye (Figure 4K). For GCM-585, the predicted habitat suitability shows a dramatic decrease, with only a few areas remaining highly suitable, exclusively in the far north (Figure 4M). This shows that climate conditions are changing and becoming less suitable. For Predicted Potential Habitat, the suitable habitat under GCM-245 is predicted to be incredibly reduced and fragmented and will be found mainly in the north (Figure 4L). Under the GCM-585 scenario, the suitable habitat is projected to be severely constrained, with only sporadic, diminutive patches remaining, primarily in northern mountainous regions (Figure 4N). This indicates a significant loss of suitable habitat across its historical range, with a northward retreat.

Discussion

Model Performance and Optimization Success

The primary goal of this study was to develop a robust and reliable predictive model for the current and future distribution of the Cilician water frog lineage in response to climate change. The model optimization process began with an initial set of 17 environmental variables. To enhance model performance and improve generalization, thereby avoiding overfitting and underfitting, the most efficient variables were selected by running the varSel and reduceVar functions. This process systematically refined the variable set by first eliminating highly correlated variables using a Spearman's rho threshold of 0.80, and then, by removing other redundant predictors. This approach follows established best practices in species distribution modeling, where the reduction of redundant variables has been shown to improve model generalization and reduce overfitting significantly (Vignali et al., 2020; Zurell et al., 2020).

The improvement in AUC values post-optimization provides substantial evidence that the elimination of less influential and correlated variables directly enhanced the model's predictive accuracy and reliability (Guisan et al., 2002). The substantial increase in both training and test AUC values after optimization is particularly noteworthy, with the model improving from an initial training AUC of 0.701 and test AUC of 0.637 to a final optimized model with a training AUC of 0.965 and a test AUC of 0.881. An initial test AUC of 0.637 suggests a model with moderate discriminatory capacity, which is considered to border on acceptable according to Navarro et al. (2010). Navarro et al. (2010) suggest an AUC above 0.7 as acceptable and above 0.8 as very good (Peterson, 2001). The optimized model's test AUC score of 0.881 is indicative of a "very good" category. This score indicates that the model can effectively distinguish between areas where the Cilician water frog lineage is present and absent (Guisan et al., 2002). In conclusion, the careful optimization process, especially the tactical minimization of environmental predictors, played a crucial role in converting a model initially exhibiting moderate performance into a highly effective and precise predictive instrument. However, it is critical to acknowledge the intrinsic limitations of MaxEnt and presence-only modeling, as they primarily map the fundamental climatic niche and do not account for critical biotic interactions or dispersal barriers. The model, which has been optimized, demonstrates robust AUC performance and provides a solid foundation for the evaluation of the impact of future climate change scenarios on the distribution of the Cilician water frog lineage (Peterson, 2001).

Key Environmental Drivers of Habitat Suitability

The application of the MaxEnt model to the Cilician water frog lineage (*P.* cf. *bedriagae* 1) successfully identified and refined the factors that significantly influence its habitat. The variable importance analyses (permutation and jackknife tests) highlighted temperature-related variables, particularly the minimum temperature of the cold quarter and the temperature seasonality, as the paramount drivers of the Cilician water frog's distribution. The exclusion of these temperature variables resulted in a significant decline in the model's predictive ability, demonstrating that they are indispensable for predicting the lineage's presence.

The validity of these results was further confirmed by the Response Curves of the variables in question (Figures 3A-3G). The Cilician water frog lineage is dependent on specific temperature conditions, making it sensitive to temperature changes, especially during periods of cool weather and seasonal shifts. Particularly, the Cilician lineage was found to be exclusively present in the Çukurova plain (Akın et al., 2010; Akın Pekşen, 2015; 2025; Plötner et al., 2001, 2010), which provides a rationale for its specific climatic requirements and adaptations in those conditions for survival and growth. This is consistent with ecological principles, as amphibians, being ectotherms, are dependent on surrounding temperatures for optimal growth, reproduction, and survival (Laurencio and Fitzgerald, 2010; Todd et al., 2010). Moreover, the modeling of the distribution of the closely related water frog species *P. caralitanus* based solely on bioclimatic variables also revealed the sensitivity to low temperature (Kıraç et al., 2022), as is also the case in the Cilician lineage. However, given that in this study the default parameters of MaxEnt were utilized without undergoing optimization, questions may be raised concerning the complete reliability of the results obtained.

Beyond temperature, ruggedness emerged as another topographic factor that exerted a significant influence, exhibiting a permutation importance value of 9.8 and strong predictive power and importance in the model's predictive ability in the results of the jackknife test. The response curve for ruggedness (Figure 3C) further clarifies this relationship, showing a high probability of presence in areas of low ruggedness and a sharp decline as ruggedness increases. This suggests that the Cilician water frog lineage may prefer flat or undulating terrain. This preference may be because these areas are more conducive to movement, offer suitable habitats for breeding, or reduce exposure to harsh conditions, aligning with extant literature on landscape attributes impacting frog habitat selection (Pilliod and Scherer, 2015; Wallace et al., 2010).

The Response Curves (Figure 3A-3G) collectively provide a comprehensive picture of the Cilician water frog's environmental niche. The strong preference for living close to the lake shows that the lineage is dependent on water or wet areas for survival and reproduction (Zero and Murphy, 2016). The positive correlation with annual rainfall at higher levels highlights their need for sufficient moisture, which is crucial for the skin's respiration and overall hydration, as evidenced by prior interpretations (Akın et al., 2010; Beerli et al., 1996; Plötner et al., 2010). Whereas slope (Figure 3D) appeared to have a consistently high probability of presence across its range, suggesting less direct limitation within the observed values, the combined influence of other topographic features, such as ruggedness, remains significant.

Current and Projected Habitat Suitability of the Cilician Water Frog in a Changing Climate

A thorough investigation into the habitat suitability and distribution of the Cilician water frog lineage has yielded significant insights into its spatial ecology and future vulnerability to climate change. The MaxEnt model successfully identified climatically suitable areas, which strongly align with the species' known geographic range in south-central Türkiye, thereby validating the model's ability to capture its fundamental niche. The predicted habitat suitability maps, in both their continuous and binary outputs, have been shown to serve as a practical tool for conservation planning. This is because they clearly delineate the core suitable region and suggest areas for further investigation. The distinction between the broader potential habitat and the more circumscribed estimated range highlights that factors beyond climate, such as dispersal barriers or land-use practices, likely influence the species' actual occupancy.

Projections of the model onto future climate scenarios (GCM-245 and GCM-585 for 2050, 2080, and 2100) consistently predict a significant northward shift in the potential habitat of the Cilician water frog lineage. This trend is evident as early as 2050, with disparities between low and high emission scenarios becoming pronounced, showing a clear decline in the extent of highly suitable areas in the historical southern range (Figures 4C-4F). This finding is consistent with the observations that amphibians exhibit high levels of environmental resilience in warm, humid climates and exhibit heightened sensitivity to climatic changes (Dufresnes et al., 2015), suggesting the possibility of a northward shift in the broader Mediterranean climate, as supported by many studies (Bağçacı et al., 2021; Boussalim and Dallai, 2024; Elverici et al., 2025). This shift has already been documented in many Mediterranean amphibian species (Elverici et al., 2025), including the closely related species *Pelophylax caralitanus* and *P. bedriagae*. These species, which are predicted to lose many habitats in southern Anatolia and gain new ones in more western and northern Anatolia (Elverici et al., 2025; Kıraç et al., 2022). Despite the challenges associated with the modeling of *P. bedriagae,* which are a result of its erroneous distribution (Elverici et al., 2025), the area is occupied by three distinct species. Additionally, the modeling of *P. caralitanus* is characterized by a lack of optimization in the model (Kıraç et. al, 2022). However, both studies emphasize the pivotal role of precipitation for *Pelophylax* species. Consequently, the specific physiological requirements of *Pelophylax* species for precipitation further imply that precipitation and temperature will be shifting northward from southeast Türkiye, with humidity being critical for the Mediterranean climate (Tuel and Eltair, 2020). Research shows that these amphibians rely on specific hydric conditions for breeding and survival, thus emphasizing their sensitivity to alterations in climate and hydrological patterns (Dufresnes et al., 2017). This indicates that, as climate patterns evolve, species such as *Pelophylax* may encounter challenges requiring careful management and conservation efforts (Dufresnes et al., 2017). By 2080 and 2100, suitable habitat will become increasingly fragmented, with the majority being concentrated in northern mountainous regions, especially under the high-emission scenario. Whereas the model projects a substantial increase in the total area of climatically suitable habitat across all future scenarios compared to the current state, it is crucial to interpret this cautiously. This increase is primarily driven by the expansion of new areas in northern Türkiye that become climatically suitable as temperatures rise, thereby offsetting the losses in the south. However, an increase in total climatically suitable area does not guarantee a proportional increase in viable habitat. This is because fragmentation of existing habitats and the challenges of successful dispersal into novel environments remain critical concerns (Loyola et al., 2013; Shrestha and Bawa, 2014). This emphasizes the distinction between a species' fundamental niche and its realized niche, particularly under rapid environmental change (Coops and Waring, 2010).

The projected shifts in habitat and fragmentation are of profound ecological significance. The observed loss of historical southern habitat will be coupled with the potential for increased isolation of remaining populations. Furthermore, populations of the Cilician water frog lineage have previously been jeopardised by overexploitation in the Çukurova Plain (Çiçek et al., 2021), thereby establishing the other significant pressure on the southern populations. The potential consequences of these processes for the historical source populations include a reduction in genetic diversity, which poses a threat to the species' long-term persistence. Furthermore, the species' expansion into new northern ecosystems raises a critical question concerning its potential to become an invasive species, with the consequence that recipient ecosystems may be impacted, although they may not be adapted to its presence. The invasive capacity of the Cilician water frog lineage has been initially documented in the native water frog populations belonging to *P. lessonae* in the western Switzerland (Dubey et al., 2014). Later, the hybridization between the Cilician water frog lineage (*P.* cf. *bedriagae* 1) with the lineage belonging to *P.* cf. *bedriagae* 2, which is distributed from western Anatolia to the Caspian Sea, has been documented in the northern border of the Çukurova plain (Akın Pekşen, 2015; 2025). Therefore, projections for the northern expansion of the Cilician lineage indicate the potential for them to act as an invasive species for northern native water frog populations belonging to *P. cf. bedriagae* 2. Consequently, all these findings emphasize the necessity for targeted, adaptive conservation strategies that must be translated into specific, prioritized management actions to mitigate negative impacts and consider the complex dynamics of species' responses to rapid environmental change. Given the predicted northward range shift and increasing fragmentation, priority should be placed on establishing and protecting hydrological and landscape corridors that facilitate species dispersal into newly climatically suitable northern regions. Simultaneously, strict measures, including enhanced enforcement and regulation, are urgently required to mitigate the dual threats of habitat degradation and historical overharvesting within the critical, high-suitability core habitats of the Çukurova Plain to secure the extant populations. This includes both the direct climatic pressures and the compounding effects of human activities such as rapid urbanization, which significantly alter regional climate balances and fragment natural habitats (Carraça and Collier, 2007; Geçen and Aytemus, 2022; Ojaghlou and Uğurlu, 2023).

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