

## ARTICLE

# Climate change effects on abundance and distribution of the European eel in Türkiye

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## Abstract

Spatial and temporal distribution of European eel (*Anguilla anguilla*) during 1967–2020 was used to model European eel distribution in response to climate variability. Modeling integrated predictions from two distinct models for inferences. First, modeling of the relationship between temperature and precipitation and European eel catch values using multiple time-series regression analyses showed that climate variables contributed to eel distribution in Türkiye. Eel catch became restricted to western and southern coasts of Türkiye and total catch decreased between 1967 and 2020. From 1967 to 2020, favorable climatic conditions for European eels in Türkiye were characterized by moderate temperatures. Furthermore, projections for 2050 and 2070 suggested that suitable habitat would be lost in Türkiye. Our findings underscore the urgent need for immediate and widespread implementation of effective conservation policies to mitigate threats to European eel in Türkiye and globally.

## KEYWORDS

climate variability, European eel, MaxEnt, multiple time series regression, species distribution modeling, Türkiye

## 1 | INTRODUCTION

The European eel (*Anguilla anguilla* L.) is a facultative catadromous species with a panmictic stock and a wide distribution from the ocean to inland water. The complex life cycle begins in the Sargasso Sea, where adults spawn and lay eggs. Leaf-shaped leptocephalus larvae drift with ocean currents to Europe, Northern Africa, and Mediterranean coasts, where they transform into glass eel larvae in coastal areas. Upon reaching estuaries, lagoons, and freshwater rivers, glass eels become pigmented elvers. Elvers reside in freshwater or brackish water for about 10 years as yellow eels. Upon reaching maturity, yellow eels transform into silver eels with several distinctive characteristics, including large eyes, larger and more pronounced pectoral fins, and thick, silver-colored skin (Aida et al., 2003; Durif et al., 2023). Yellow eels return to

the Sargasso Sea, where they spawn and complete their life cycle (Tesch, 2003).

In freshwater, eels rely on favorable habitats from small ponds and streams to large lagoons, lakes and rivers for their life cycles (Tesch, 1977), which makes them particularly vulnerable to impacts of climate change (Robinson et al., 2009). Related to climate change, shifts in characteristics of specific sites are critical for catadromous fish, by disrupting their distribution (Rushing et al., 2020). Recent stock assessments indicate a rapid decline from the 1980s to present (ICES, 2022). Therefore, the European eel was listed as “Critically Endangered” in the IUCN Red List of Threatened Species since 2000 and is included in CITES Annex II (IUCN, 2022). Anthropogenic impacts, including habitat destruction, migration barriers, hydropower, invasive species, pollution, and fishing, along with environmental changes, contribute

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to declining eel abundance (Correia et al., 2018; ICES, 2022; Kettle et al., 2011). In addition to a general decline in abundance, recruitment from the larval stage in the ocean to the growth phase in freshwater varies among regions. For example, recruitment declined more in the North Sea than in the rest of Europe (ICES, 2022). Locally, yellow eel stock size increased in five of eight reference areas in the German part of the southern Baltic Sea during 2009–2020 but declined in three eel management areas in Türkiye (Dorow et al., 2023; Yalçın Özdilek & Özdilek, 2020). Regional differences in eel abundance may have resulted from spatial variation in climate change. For example, river discharge, a key factor in silver eel migration, may be impacted by local climate-induced long-term changes that alter migration patterns (Acou et al., 2008; Arevalo et al., 2021; Drouineau et al., 2017; Durif et al., 2002). Climate change and variability has impacted the freshwater parts of the eel life cycle in Europe (Arevalo et al., 2021; Barbarossa et al., 2021; Bonhommeau et al., 2008; Borges et al., 2019; Carpenter et al., 1992; Jarić et al., 2019; Morales-Marín et al., 2019). However, the relationship between local eel catch and specific climate events, such as extreme changes in temperature and precipitation, has not yet been quantified.

Climate change is a primary driver of environmental change in freshwaters, including the Mediterranean Basin. Temperature increases and precipitation variability are two components of climate change, especially in the semi-arid Mediterranean climate, where temperature is estimated to increase 0.36°C per year during 1982–2012 (Shaltout & Omstedt, 2014) and a 1–7°C mean global temperature increase will result in regional changes in hydrological regimes and water physicochemical characteristics (Ficke et al., 2007). As a Mediterranean country, Türkiye has an extensive network of streams that are highly susceptible to climatic conditions and are expected to be affected by precipitation variation (Bayazit & Avci, 1997). Significant fluctuations in stream flows are attributed to seasonal precipitation patterns and changes in hydrological cycles (Arevalo et al., 2021; Cigizoglu et al., 2005; Morales-Marín et al., 2019). In addition, sudden temperature fluctuations can cause behavioral and physiological changes in fish species by affecting energy gains and nutrition rates (Allan et al., 2015; Moretto et al., 2022; Nagelkerken & Munday, 2016).

Predictions linking climatic conditions to distribution models must incorporate temporal and geographical aspects to be site-specific and science-based. This is important because long-term climate variability will change the distribution patterns of local stocks. Species distribution models are now commonly used to predict changes in species distributions in response to climate change, but such stand-alone use falls short of yielding intended results. Modeling species distribution in relation to climate variables estimates variables that are most influential for species survival in a specific habitat, by assuming the relationship between species occurrence over time and changes in climate variables or extreme

events can predict future population structure. However, substantial future changes in climate parameters raise concerns about prediction and interpretation accuracy (IPCC, 2022). Studying the link between species occurrence over time and extreme climate events or changing climate variables and discerning positive and negative climatic conditions impacting species in respective habitats, will significantly contribute to conservation-focused sciences. Therefore, using multiple time series regression analysis, species distribution models, and critical thresholds may be useful for assessing responses of the European eel to climate change on a local scale.

Our objective was to determine if eel abundance was related to climate variation in Türkiye during 1967–2020, as a potential predictor of future climate change effects on eels in Türkiye and elsewhere in the world. To achieve our objective, we first quantified spatial and temporal variation of eel catch data, as an index of eel abundance, at the provincial level in Türkiye during 1967–2020. Next, we examined temporal climate variability in provinces, from temperature and precipitation indices during 1967–2020, to estimate break points of sudden temporal change. We then tested the relationship between eel catch data and temperature and precipitation indices during 1967–2020, to predict the distribution of European eels in 2050 and 2070. We used our findings to suggest solutions for conserving, managing, and sustaining European eels in the future in Türkiye and elsewhere in the world.

## 2 | MATERIALS AND METHODS

### 2.1 | Species data (catch and occurrence data)

Catch data were used as an index of eel abundance. Catch data overestimate population abundance and density due to increased fishing impact on the European eel since the turn of the 20th century, but provides information about the stock of the European eels throughout their distribution area (Aalto et al., 2016). Therefore, catch data could be a useful index for understanding regional and temporal variation in eel abundance, and for testing a relationship to climatic factors, for predicting future abundance in response to continuing climate change.

Annual catch of eels in provinces was obtained from the Turkish Statistical Institute (TUIK, 2021). Catches of European eels were obtained from 51 provinces in Türkiye with the most prominent eel fishing areas, classified as eel management areas (EMA1, EMA2, and EMA3) along the coastline and across central regions of Türkiye (Yalçın Özdilek & Özdilek, 2020). Catches included Black Sea areas (EMA4) from 1967 to 2020. First, catch data from 1967 through 2020 at a provincial scale (Yalçın Özdilek & Özdilek, 2020) were joined to a Türkiye province administrative shapefile. Then, cumulative sums were calculated for each province during 1967–2020 and shorter periods (1967–1988, 1989–1998, 1999–2010,



and 2011–2020). Maps displaying cumulative eel catch for each province were generated using ArcMap for each temporal period. Lengths of eels in catch records obtained from TÜİK were 50 cm and longer. Recorded specimens did not fully represent silver eels, so proportions of yellow and silver eels were uncertain.

The occurrence data, produced availing of direct observation, literature and gray data, were collected from the 51 provinces where the catch data were collected. The coordinates of 279 eels throughout Türkiye were collected, as an index of occurrence to determine effects of climatic variables. Some eel locations also included coordinates that coincided with those collected by the General Fisheries Commission for the Mediterranean (GFCM) (Ciccotti & Morello, 2023). Background pseudo-absence locations where the species has not been observed but are used in the model as if the species is absent were also generated to account for sampling bias, as recommended by Barbet-Massin et al. (2012). While generating the pseudo-absence locations, geographical and climatic conditions were taken into consideration and randomly selected outside the suitable area of the species and not too close to a point where it was seen.

## 2.2 | Environmental data

The Climate Change Detection and Indices Expert Team developed 27 descriptive daily extreme precipitation and temperature weather event indices (<http://cccma.seos.uvic.ca/ETCCDMI>). Gonencgil and Acar (2021) and Acar and Gönençgil (2022) generated 16 precipitation and temperature indices from these indices and used them to investigate effects of climate variability on distribution of European eel in Türkiye (Table 1).

Environmental predictors from the WorldClim database (<http://www.worldclim.org>; Hijmans et al. (2005)) were used to model eel distribution in species distribution models (Table 2). WorldClim version 2.1 (January 2020) included bioclimatic variables interpolated from climate data during 1970–2000 at a spatial resolution of 2.5 arc-minutes (~5 km) (<https://www.worldclim.org/data/worldclim21.html>) (Table 2).

## 2.3 | Data analyses

### 2.3.1 | Regression analysis of change in catch time series data

Prior to data analysis, Augmented Dickey-Fuller (ADF) (Cheung & La, 1995) and Kwiatkowski-Phillips-Schmidt-Shin (KPSS) (Kwiatkowski et al., 1992) tests were used to validate the stationarity assumption. Following validation, simple linear regression was used to test whether eel catch changed linearly over time during 1967–2020 (Hyndman & Athanasopoulos, 2018):

$$y_t = \beta_0 + \beta_1 x_t + \varepsilon_t \quad (1)$$

where  $t$  = year (1967–2020),  $y_t$  = predicted catch in year  $t$ ,  $\beta_0$  = the intercept,  $\beta_1$  = the slope of average expected change per year in predicted catch,  $x_t$  = observed catch in year  $t$ , and  $\varepsilon_t$  = unexplained error.

### 2.3.2 | Examining the temporal change of climate index and calculating breakpoints

Climate index information recorded from the meteorology stations between 1967 and 2014 was used in the regression model (in Equation 1) following the stationarity assumption checks to ascertain whether there was a temporal change and trend. Breakpoint estimates, which indicate significant changes in temperature and precipitation in both data sets, were carried out using the Zivot-Andrews test (Zivot & Andrews, 1992).

### 2.3.3 | Assessing the relationship between climatic indices and catch data

Effects of the climate variables on eel catches during 1967–2014 were examined utilizing multiple time series regression analysis (Hyndman & Athanasopoulos, 2018):

$$y_t(t) = \beta_0 + x_t^T \beta_i(t) + \varepsilon_i(t) \quad (2)$$

where  $\{x_t = (x_{t1}, x_{t2}, \dots, x_{tm})^T\}$  = a set of random explanatory variables (climate indices) of  $m$ -dimensions,  $\{\beta_i = (\beta_{i1}, \beta_{i2}, \dots, \beta_{im})^T\}$  = a  $m$ -dimensional parameter vector,  $y_t(t)$  = the random variable series for year  $t$ , and  $\varepsilon_i(t)$  = unexplained error for year  $t$ . Stepwise regression analysis was used to select the most appropriate model of the relationship between catch and climatic indices in the entire area and in individual management units. Regression models for the entire area and each management unit included selected variables and predicted breakpoints as dummy variables.

### 2.3.4 | Species distribution modeling

Species Distribution Models (SDMs) were used to model mathematical relationships between species presence and corresponding environmental variables and to predict the spatial distribution across a location of interest (Shi et al., 2022). SDMs visually depict a species range in different periods to assess its response to climatic conditions. Among SDM methods, MaxEnt (maximum entropy) is widely used and highly accurate, especially for limited species occurrence data (Gomes et al., 2018; Kaky et al., 2020; Merow et al., 2013; Radosavljevic & Anderson, 2014; Yoon & Lee, 2021).

Distribution of eels was modeled over the entire area. Selected bioclimatic variables were determined using the *SDM tune* package in R (Vignali et al., 2020). The MaxEnt algorithm, a general-purpose machine learning approach for modeling species' geographic

Index	Descriptive name	Definition
SU	Summer days	Annual number of days when TX (daily maximum temperature) > 25°C.
TR	Tropical night	Annual number of days when TN (daily minimum temperature) > 20°C.
TX99p	Extremely hot days	Percentage of time when daily max temperature > 99th percentile
TX95p	Hot days	Percentage of time when daily max temperature > 95th percentile
TX90p	Warm days	Percentage of time when daily max temperature > 90th percentile
TX05p	Cold days	Percentage of time when daily max temperature < 05th percentile
TX01p	Extremely cold days	Percentage of time when daily max temperature < 01st percentile
WSDI	Warm spell duration index	Annual number of days with at least 5 consecutive days when TX > 95th percentile
CSDI	Cold spell duration index	Annual number of days with at least 5 consecutive days when TN < 5th percentile
DTR	Daily temperature range	Monthly mean difference between TX and TN
R99p	Extremely wet day rainfall	Annual total precipitation (PRCP) when daily rainfall (RR) > 99th percentile
R95p	Very wet days rainfall	Annual total precipitation when daily rainfall (RR) > 95th percentile
SDII	Simple daily intensity index	Annual total precipitation divided by the number of wet days in the year; wet days defined as PRCP ≥ 1.0mm
CDD	Consecutive dry days	Maximum number of consecutive days with daily precipitation < 1mm
CWD	Consecutive wet days	Maximum number of consecutive days with daily precipitation ≥ 1 mm

**TABLE 1** Definitions of temperature and precipitation indices used to model European eel (*Anguilla anguilla*) abundance and distribution in Türkiye during 1967–2020 (as in Gonencil and Acar (2021) and Acar and Gonençgil (2022)).

distributions, was used to model current and future potential distributions of eels in relation with habitats (Phillips et al., 2006). Default settings of MaxEnt can produce reliable forecasts with little parameter modification, by locating the probability distribution with the highest entropy, to estimate a target probability distribution (Li & Wang, 2013).

The amount of relevant information that each bioclimatic variable contributed to the MaxEnt model was used as a criterion to select predictors. Unassociated variables, occurrence records, and a randomly chosen background across raster layers were used to create the model. All variables that contributed more than 3% were selected for analysis using the *dismo* package in R (Hijmans et al., 2022).

### 2.3.5 | Forecasting future distribution of eels

The Community Climate System Model (CCSM4) version 4, which provides research on existing and future climate conditions, was used to predict future distributions of eels. Climate scenarios were based on two Representative Concentration Pathways (RCP) that are used in climate modeling and research to predict possible future climatic scenarios based on current greenhouse gas (GHG) emissions (van Vuuren

et al., 2011). RCP 4.5 was selected as an intermediate scenario that assumed an intermediate level of GHG emissions and projects average temperature increases of 0.9–2.0°C. RCP 8.5 was also selected as the most pessimistic scenario that assumed a higher level of GHG emissions and projects increased mean global temperature of 1.4–2.6°C by the 2050s. Future projections used bioclimatic data from 2050 (average during 2041–2060) and 2070 (average during 2061–2080).

The model was trained and evaluated using 5-fold spatial block cross-validation, which split the study scope into 100 km × 100 km spatial blocks and assigned each block to one of five cross-validation segments (Gaul et al., 2020; Roberts et al., 2017). Model performance was evaluated using: (1) a threshold-independent area under the curve (AUC); and (2) Cohen's Kappa calculated using the threshold that maximized Kappa (Berrar, 2018; Fielding & Bell, 1997; Gaul et al., 2020). Model accuracy with potential thresholds was indicated by the AUC (range = 0 to +1), with values greater than 0.5 indicating the model performed better than a random guess, and values close to 1 indicating more descriptive, sensitive, and better discriminating models (Kaky et al., 2020; Phillips et al., 2015). A kappa statistic (range = 0 to +1) of +1 indicated perfect concordance and ≤ 0 indicated random performance (Ahmed et al., 2021; Berrar, 2018).

**TABLE 2** Bioclimatic variables acquired from the WorldClim database used for modeling European eel (*Anguilla anguilla*) abundance and distribution in Türkiye during 1967–2020.

Bioclimatic variables codes	Bioclimatic variables
Bio 1	Annual Mean Temperature
Bio 2	Mean Diurnal Range
Bio 3	Isothermality (Bio2/Bio7)*100
Bio 4	Temperature Seasonality (standard deviation*100)
Bio 5	Max Temperature of Warmest Month
Bio 6	Min Temperature Coldest Month
Bio 7	Temperature Annual Range (Bio5-Bio6)
Bio 8	Mean Temperature Wettest Quarter
Bio 9	Mean Temperature Driest Quarter
Bio 10	Mean Temperature Warmest Quarter
Bio 11	Mean Temperature Coldest Quarter
Bio 12	Annual Precipitation
Bio 13	Precipitation of Wettest Month
Bio 14	Precipitation of Driest Month
Bio 15	Precipitation Seasonality (Coefficient of Variation)
Bio 16	Precipitation of Wettest Quarter
Bio 17	Precipitation of Driest Quarter
Bio 18	Precipitation of Warmest Quarter
Bio 19	Precipitation of Coldest Quarter

The logistic output from the MaxEnt algorithm classified environmental adaptability of eels from 0 (unsuitable) to 1 (suitable, or optimal). While generating potential distribution maps, four threshold values were used for the distribution area, and habitats were classified as unsuitable, ( $\leq 0.10$ ), low potential (0.11–0.30), moderate potential (0.31–0.70), and high potential ( $\geq 0.71$ ) (Abdelal et al., 2019). The open-source programming language R version 4.3.1 (R Core Team, 2023) was used for computation and visualization, and statistical significance was assumed if  $p \leq 0.05$ .

### 3 | RESULTS

#### 3.1 | Spatial variation of eel catch data recorded between 1967 and 2020

Eel catches were higher in provinces across the Aegean and the Mediterranean Regions. This region included three main fishery habitats, including Bafa Lake in EMA1 (Aydın), Köyceğiz Lagoon system in EMA2 (Muğla), and Yumurtalık Lagoon in EMA3 (Adana). Total eel catches in these three provinces (7,472,193 kg) accounted for 47% of total eel catches in the country over a 54-year period (Figure 1).

#### 3.2 | Temporal variation of eel catch data recorded between 1967 and 2020 and breakpoints

Catches were not stationary in all study areas (ADF  $p > 0.05$ ; KPSS  $p < 0.05$ ), which supported validity of model assumptions. Stationarity was attained by differencing each series. Catches varied temporally in all areas (ADF  $p = 0.731$ ; KPSS  $p = 0.01$ ), EMA1 (ADF  $p = 0.2618$ ; KPSS  $p = 0.01$ ), and EMA2 (ADF  $p = 0.9357$ ; KPSS  $p = 0.03$ ), but not in EMA3 (ADF  $p = 0.02$ ; KPSS  $p = 0.1$ ) and EMA4 (ADF  $p = 0.031$ ; KPSS  $p = 0.1$ ). In all areas, breakpoints were evident in 1988, 1998, and 2010. Breakpoints differed slightly among management units, but 1988 was a critical breakpoint in EMA1, EMA2 and EMA4, which are all located in northern Türkiye (Black Sea, Marmara, and Northern Aegea). Breakpoints in EMA2 and EMA4 were earlier (1983 and 1984) than in other areas. European eel catches in the entire area (EMA1 and EMA2) decreased significantly over time (Figure 2; Table 3).

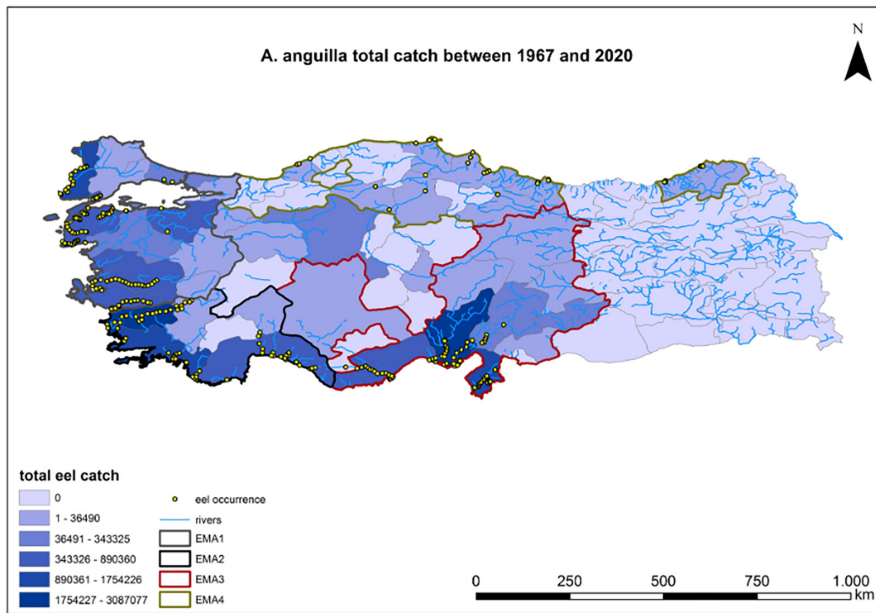
In EMA1, catches began to decrease in 1988, with a minor increase in 1993, and little change thereafter (Figure 2). In EMA2, catches decreased in 1983, 1987, and 2010, but not in 1993. In EMA3, catches increased substantially in 1980, and declined twice thereafter. In EMA4, catches varied irregularly, with no significant breakpoints. Breakpoints were not significant due to a lack of records in relevant regions. Cumulative eel catches decreased and became restricted to western and southern coasts of Türkiye during 1967–2020 (Figure 3).

#### 3.3 | Modeling the relationship between climate indices and the number of eel catches

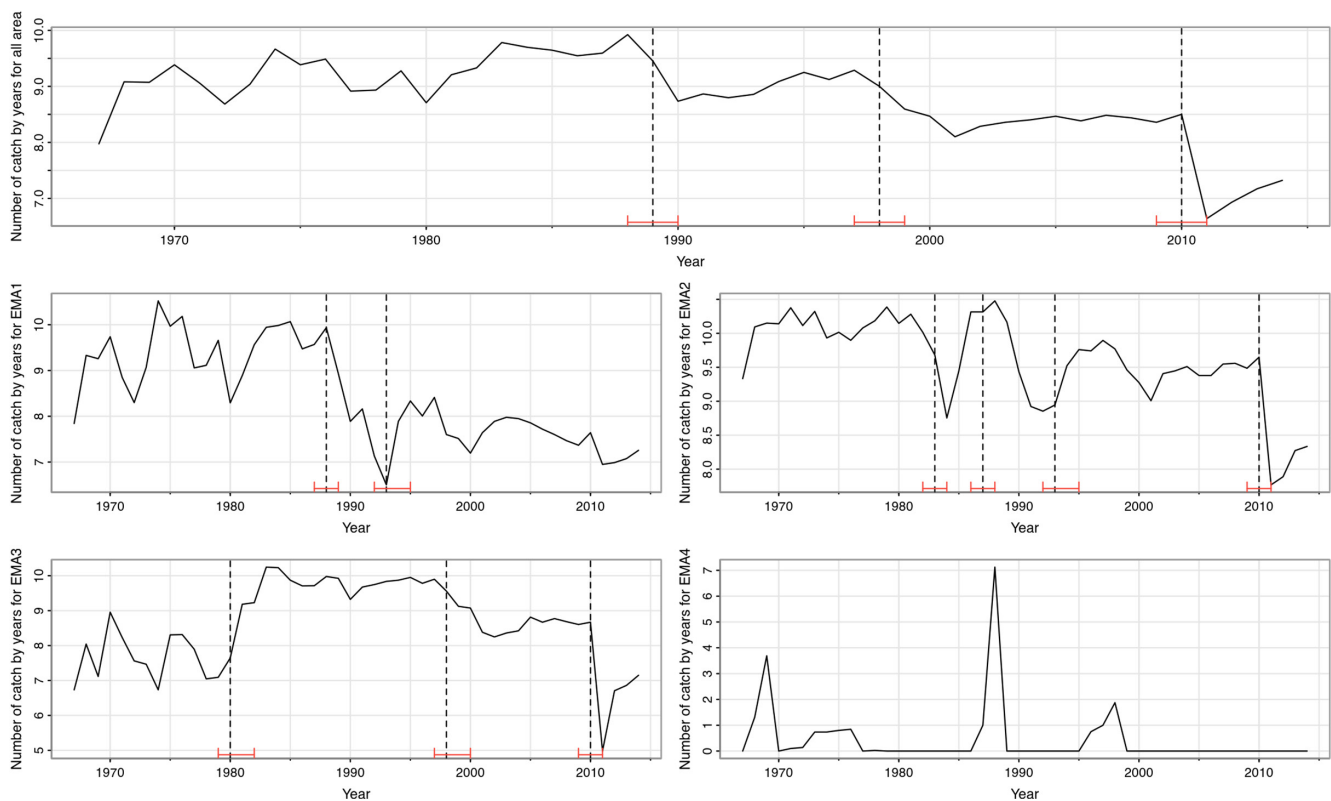
Climatic indices were not stationary (ADF  $p > 0.05$ ; KPSS  $p < 0.05$ ) and some climatic variables were significantly related to eel catches in the entire area and in each EMA during 1967–2014 (Table 4; Figure 4). The tropical night index (TR, nighttime temperatures greater than 20°C) was significantly related to decreased eel catches in the entire area, with a significant breakpoint in 1988 ( $p < 0.001$ ). In EMAs, the tropical night index (TR) was negatively related to eel catches in EMA1 and EMA2 ( $p < 0.001$ ). Eel catches were also negatively related to hot days (TX95p) in EMA2 and EMA3 and extremely hot days (TX99p) in EMA3. Eel catches were also positively related to extremely cold days (TX01p) in EMA2 and cold days (TX05p) in EMA3. A breakpoint in 1988 in declining eel catches was significant for all of Türkiye and EMA1. In EMA2, a breakpoint in 1989 in declining eel catches was significant.

#### 3.4 | Species distribution modeling

Five of 19 environmental predictors were most predictive of eel distribution in Türkiye during 1967–2020 (Figure 5). Minimum temperature of the coldest month (Bio 6) explained 38.66% and mean temperature of the coldest quarter (Bio 11) explained



**FIGURE 1** Total catches (kg) of European eels (*Anguilla anguilla*) in Türkiye during 1967–2020.



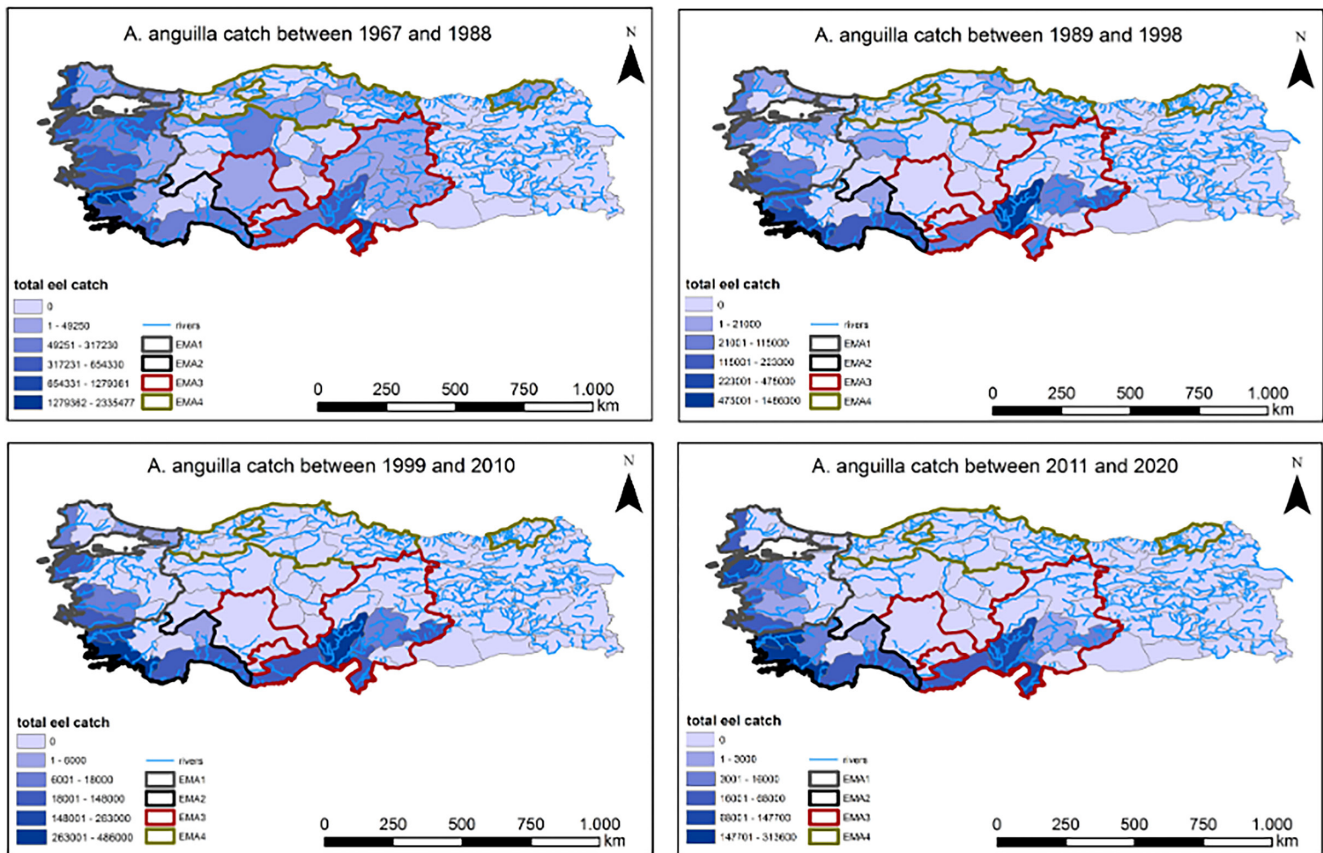
**FIGURE 2** Eel catches (kg) of European eels (*Anguilla anguilla*) in Türkiye (upper panel) and management areas EMA1–EMA4, with breakpoints (vertical lines), during 1967–2020. Red lines on the x-axis indicate confidence intervals of breakpoints.

36.78% of eel distribution. Temperature seasonality (Bio 4) explained 11.72%, precipitation of driest quarter (Bio 17) explained 9.44%, and annual precipitation (Bio 12) explained 3.4% of eel distribution. The eel distribution model outperformed random prediction ( $AUC > 0.5$ ), and had high predictive ability ( $Kappa = 0.77$ ) for both training data ( $ROC = 0.949$ ) and testing data ( $ROC = 0.946$ ).

The extent of suitable habitat for eels, when compared to the current distribution of eels, declined progressively in 2050 and 2070 (Figure 6). By 2050, habitat suitability decreased from 72% at present to 34% for the optimistic climate-change scenario and 27.3% for the pessimistic climate-change scenario. By 2070, habitat suitability decreased to 28.2% for the optimistic climate-change scenario and 14.5% for the pessimistic climate-change scenario.

**TABLE 3** Parameter estimates of temporal trends and breakpoints of European eel (*Anguilla anguilla*) catches in Türkiye (all area) and management areas (EMA 1–EMA4) during 1967–2020.

	Beta estimate (std. error)	p_value	Trend estimate (std. error)	p_value	Breakpoints
ALL AREA	-0.040 (0.006)	0.000	-0.03 (0.01)	0.012	1988, 1998, 2010
EMA1	-0.061 (0.008)	0.000	-0.039 (0.015)	0.04	1988, 1993
EMA2	-0.03 (0.005)	0.000	-0.037 (0.01)	0.001	1983, 1987, 1993, 2010
EMA3	0.003 (0.012)	0.832	-0.044 (0.013)	0.052	1980, 1998, 2010
EMA4	-17.37 (12.23)	0.162	-0.002 (0.302)	0.128	1984, 1988



**FIGURE 3** European eel (*Anguilla anguilla*) catches in Türkiye between breakpoints (1988, 1998, and 2010) during 1967–2020.

## 4 | DISCUSSION

European Eels in Türkiye were primarily concentrated in well-known lakes and lagoons along the Aegean and Mediterranean coastal regions during 1967–2020, but shifted in distribution since the 1960s, particularly in 1988 and 1989, when abundance declined significantly, except in the Black Sea Region, where no eels were caught after 2010. Historical catches were periodic in certain provinces before 1988, and ranged 2–6 consecutive years, but were sporadic in other provinces. Although our study did not identify causes of eel population declines, human impacts, such as urbanization-induced habitat degradation and dam development, might be associated with this downward trend (Haro et al., 2000). More research is needed

to determine if anthropogenic impacts were associated with the reduction in eel catches in Türkiye. Eel catches in Türkiye declined significantly since 1980, with large breakpoints, concurrently with an increase in global warming, which underscores the potential impact of environmental breakpoints on eel populations (Haeberli & Beniston, 1998). The frequency of climate warming and subsequent water warming, which threaten the sustainability of the European eel, have tended to increase in summer for the last 30 years.

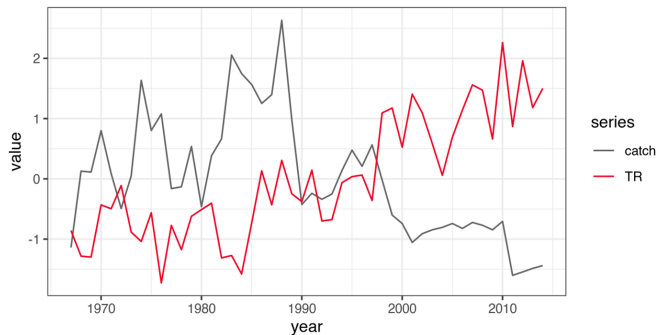
In the context of rapid climate variability, species' dispersal tendency in a region may be attributed to their evolutionary responses to environmental gradients over time (Parmesan, 2006). The adaptive capacity of a species is crucial in determining its ability to maintain or alter its geographic occurrence in changing climatic

Models	Parameter	Estimate	Std. error	p-value	Adj. R <sup>2</sup>
Entire Area (TÜRKİYE)	Intercept	10.401	0.234	2.00E-16	0.59
	TR	-0.06	0.008	2.08E-08	
	Brk_88	-1.831	0.467	0.0003	
EMA1	Intercept	10.043	0.198	2.00E-16	0.52
	TR	-0.054	0.008	2.94E-08	
	Brk_88	-0.32	0.511	0.0107	
EMA2	Intercept	12.07	0.849	2.00E-16	0.45
	TR	-0.143	0.08	0.0275	
	TX01p	0.147	0.066	0.032	
	TX95p	-0.058	0.018	0.002	
	Brk_89	-1.563	0.516	0.004	
EMA3	Intercept	10.517	0.669	2.00E-16	0.39
	TX95p	-1.02	0.424	0.021	
	TX05p	0.08	0.034	0.019	
	TX99p	-0.158	0.047	0.002	

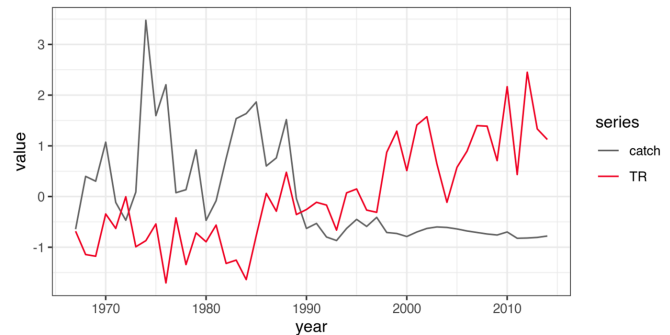
**TABLE 4** Parameter estimates of modeling relationship between catch and climate index series for the entire area and management units.

Note: Intercept: Regression constant, TR: Tropical night, TX01p: Extremely cold days, TX95p: Hot days, TX05p: Cold days, TX99p: Extremely hot days, Brk\_88: Breakpoint in 1988, Brk\_89: Breakpoint in 1989.

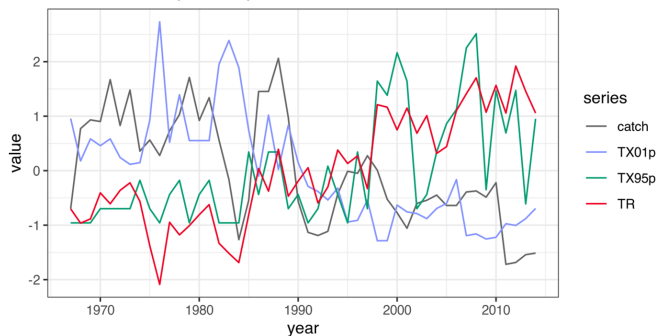
**(a)** Catch vs TR for the all area



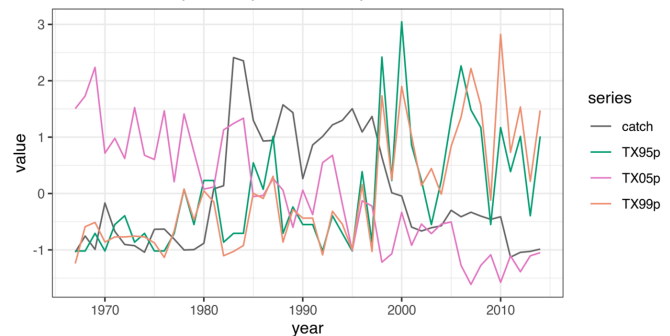
**(b)** Catch vs TR for the EMA1



**(c)** Catch vs TX01p, TX95p, and TR for the EMA2



**(d)** Catch vs TX95p, TX05p, and TX99p for the EMA3

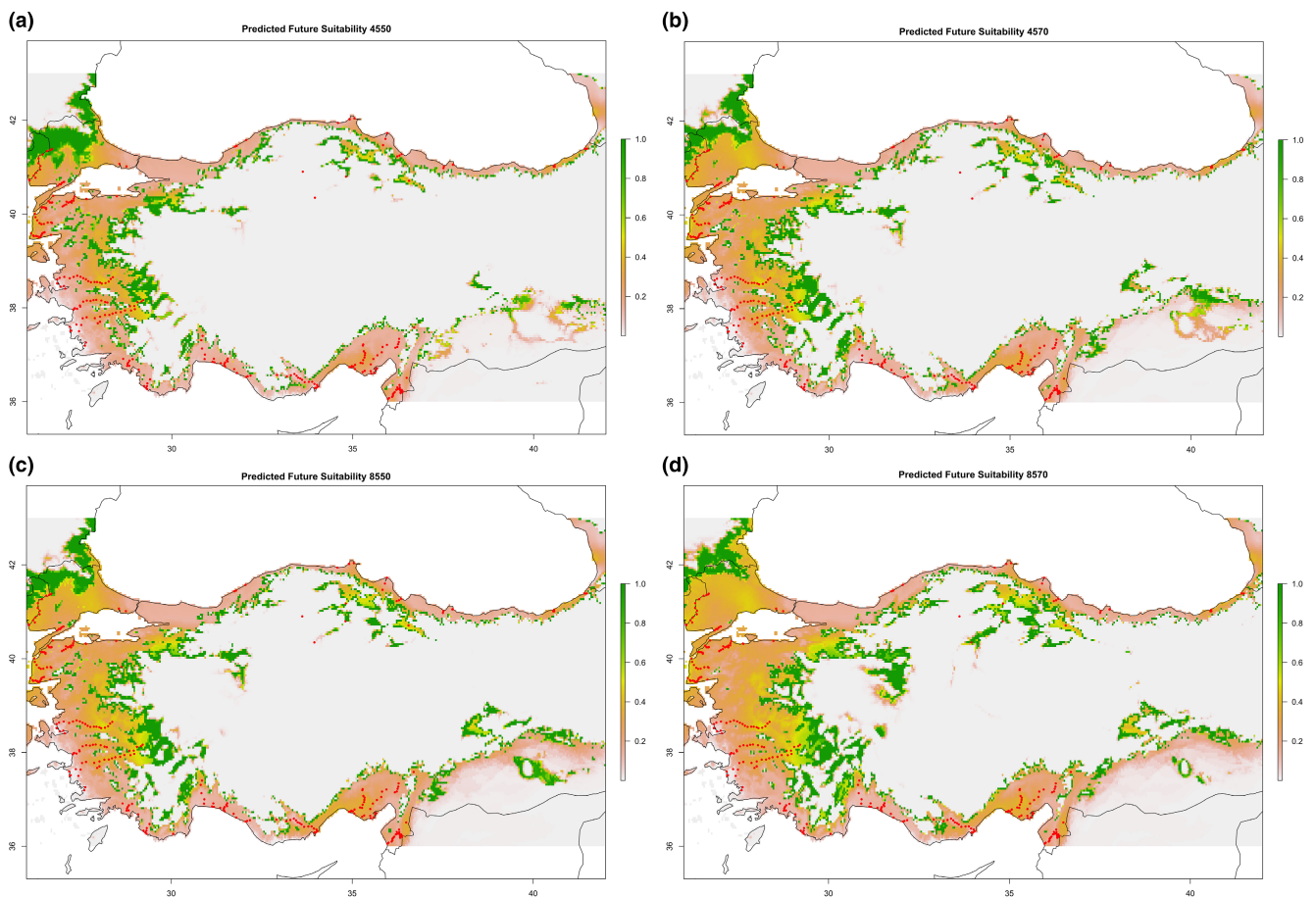
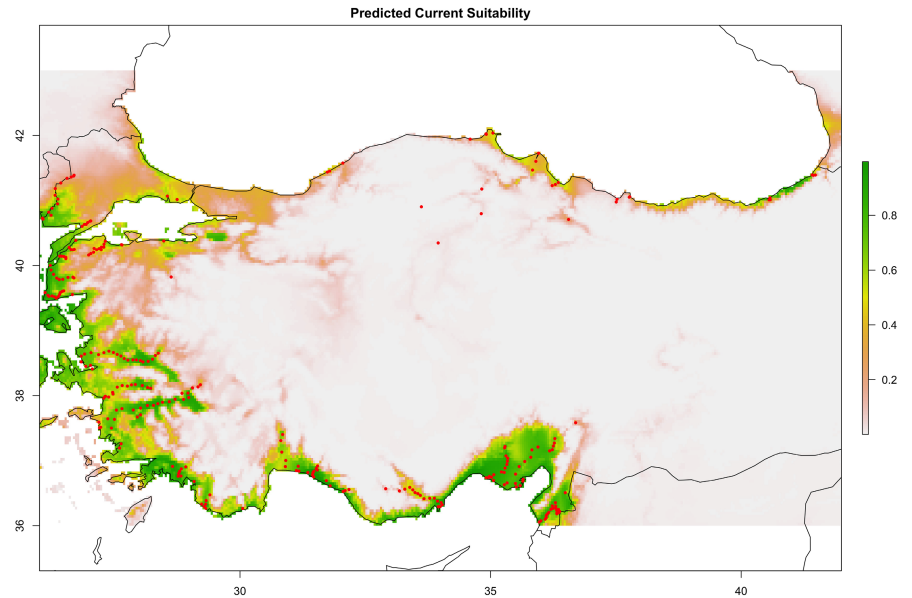


**FIGURE 4** Catches of European eels (*Anguilla anguilla*) and independent climatic variables (see Table 1) in all areas (a), and areas EMA1 (b), EMA2 (c), and EMA3 (d) in Türkiye during 1967–2020.

conditions (IPCC, 2014). The adaptive capacity of a species to climate change is associated with factors including its distribution, movement, demographic structure, life history characteristics, abiotic niche, ecological role and evolutionary potential (Thurman et al., 2020). Persistence in place and shifting in space are two main determinants of the adaptive capacity of a species to climate

variability (Thurman et al., 2020). The European eel has an advantage in its adaptive capacity due to its wide distribution and movement complexities. However, we found that local climatic variables would likely restrict its future distribution at the southern edge of its range. Further, considering its life history and demographics, the European eel's ability to adapt to changing climates in its natural

**FIGURE 5** Current distribution of the European Eel (*Anguilla anguilla*) in Türkiye based on catches during 1967–2020. Threshold values of 0.00–0.10 (white) are unsuitable, 0.11–0.30 (orange) have low potential, 0.31–0.70 (light green-yellow) have moderate potential, and 0.71–1.0 (green) have high potential habitat. Red dots indicate species presence (sampling points).



**FIGURE 6** Future habitat suitability for the European Eel (*Anguilla anguilla*) in Türkiye based on species distribution modeling in relation to projected climate change in 2050 and 2070 under global climate change scenarios RCP4.5 and RCP8.5.

local habitat remains uncertain (Barewar et al., 2023). The silver eel stage may be more susceptible during migration, which coincides with periods of extreme climatic fluctuations, particularly in summer and autumn, when nocturnal temperatures exceed 20°C

(Bašić et al., 2019). Therefore, movement patterns, particularly migration timing, can make this species vulnerable during the silver eel stage. Migration, predominantly within a narrow period (less than a month in a year) in groups, might expose the species to rapid climate

change (Bruijs & Durif, 2009). For example, a hydropower station in Germany recorded 90% of eel catches within a 10-day period (Bruijs et al., 2003). This restricted migration time is attributed to physiological readiness of eels depending on silvering processes (Bruijs & Durif, 2009), which are triggered by environmental variables such as water level and temperature (Sandlund et al., 2017). While water level is positively related to numbers of migrant eels, a succession of drought conditions may impede migration (Deelder, 1984; Frost, 1950; Haro, 2003; Sandlund et al., 2017; Trancart et al., 2013). Lack of seasonal catch data that inhibits analysis of migration timing underscores a need to collect data on seasonal catches to enhance management strategies for species that exhibit time-limited migratory patterns as a response to climate change.

We found that temperature-related indices were significantly related to catches of European eels across all regions and areas in Türkiye. The positive relationship between extremely cold days and eel catches we found aligned with reports that migration occurs when temperatures decline (Bruijs & Durif, 2009). The preferred migration temperature of silver eel ranges from 10°C to 20°C (Arevalo et al., 2021), consistent with our identification of TX01p as the optimum eel migration temperature. Additionally, the predicted negative relationship between eel catches and TR, TX95p and TX99p indicates that persistent increases in such weather events over time significantly affected landings. Considering the optimal migration temperature, this outcome was expected. In 2022, the summer average temperature was 24.6°C, which was 0.6°C higher than the long-term average temperature in Türkiye (Turkish State Meteorological Service (TSMS), 2023). Elevated summer temperatures in Turkish waters pose a threat to eel habitat, and our findings indicate that rising surface temperatures significantly reduced eel habitat quality, and thereby increased the vulnerability of the temperature-sensitive eel population, by impacting overall quality of their habitat and growing conditions.

MaxEnt is a valuable tool for predicting the future distribution of other fish species with wide-ranging patterns using long-term catch data (Kim et al., 2020). However, MaxEnt relies on current or past bioclimatic variables, by assuming a positive relationship with species presence, and thereby potentially overlooking negative relationships. Some climate variables may be negatively related to species presence, and may indicate that species presence will decrease in the future. Therefore, MaxEnt may estimate climatic factors that are positively related to the presence of species as contributing variables, while not assessing negatively related variables as low or non-contributors. However, ignored variables may be more important when developing a conservation approach. To address this, the present study used MTSRA to understand the bidirectional nature of the relationship between climate variables and catches. For example, MTSRA revealed a negative relation between temperature and species presence that MaxEnt may have masked. The number of nights with minimum temperatures above 20°C provides important information for developing effective eel conservation strategies. For instance, in the framework of continuously monitoring water temperature of core habitats of the European eel, it may be necessary to adapt barriers in line with observed temperature levels.

The findings of MTSRA reveal that, within the context of Turkish conditions, five climate variables, all of which are temperature-related, demonstrate a significant relationship with the catch data. The result of MaxEnt supported this finding and temperature was the most important variable (87.16%) for the European eel distribution model. This finding supports the studies of Allan et al. (2015), Nagelkerken and Munday (2016), and Moretto et al. (2022). Based on the identified variables that are crucial for determining the appropriate habitat conditions for eel in this geography, it can be argued that a rise in temperature is not a favorable condition for the European eel. Factoring in RCP 4.5 and RCP 8.5, it is expected that the suitable habitat area for the European eel in Türkiye will decrease significantly in the coming years. The results of the modeling conducted with respect to weather events and the MaxEnt algorithm suggest that the warming trend poses a significant threat to the European eel, particularly in its continental habitat. Climate change has raised water temperatures and altered seasonal rainfall patterns in several rivers, affecting hydrological processes (Wang et al., 2023). In Türkiye, the frequency of days when the temperature is above 20°C increases in summer and autumn (Goncengil & Acar, 2021). The silvering process begins in autumn, which coincides with the start of precipitation (Van Ginneken et al., 2007). Nevertheless, droughts persist in streams and interconnections between lakes and lagoons (Bond et al., 2008). If the silver eel starts migrating in response to rainfall, extreme temperatures will halt migration due to unfavorable physical conditions, and confine eels in isolated water bodies, where a hypertrophic crisis will ultimately lead to their death or increase their vulnerability to predation and capture.

The Intergovernmental Panel on Climate Change (IPCC) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) highlighted risks posed by climate change, and thereby emphasized the urgent need for action to protect biodiversity and mitigate impacts (Shi et al., 2022). Even a modest 1.5°C global warming is a significant threat to many freshwater species and ecosystems currently on the verge of extinction (Capon et al., 2021). Without timely protective measures, we found that the stability and sustainability of European eel habitat in Türkiye may rapidly decline. Proposed sanctions aiming for a 1.5°C target, set in the 2015 COP21 Paris Agreement, are aimed at reducing risks to freshwater ecosystems, but some proposed sanctions (dams, increased water demand for cooling, increased hydroelectric power generation, carbon sequestration fields) also threaten freshwater ecosystems (Shi et al., 2022). Climate action plans that prioritize freshwater ecosystems crucial for services like freshwater supply are needed. While mitigating climate change is challenging, directing efforts towards achievable goals within complex climatic circumstances, particularly in the primary habitats of the European eel, is advisable.

The European eel is an economically and ecologically important species due to its unique biological and ecological characteristics, and its population is declining in Türkiye. We found that climate change will likely reduce the distribution and abundance



of European eel in the southern extent of its distribution area. Although the European eel has a broad geographical range, contrasting environmental conditions, unfavorable thermal conditions, and increasing temperature will likely affect its distribution, and unfavorable conditions are expected to increase in frequency in coastal eel habitats in the future. In addition to fisheries, enhanced habitat-based conservation strategies are needed to foster development of appropriate large-scale adaptation strategies for European eels, which contribute greatly to ecosystem services. Given the inevitability of climate change, we recommend extensive studies to facilitate in-situ conservation efforts. These studies should focus on predicting effects of climatic variables that impact sustainable population and migratory behavior of eels, especially within key habitats.

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## CONFLICT OF INTEREST STATEMENT

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 STATEMENT

Data available on request from the authors.

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