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Species distribution models of Türkiye's endemic genus: *Seminemacheilus* Banarescu & Nalbant, 1995 (Cypriniformes: Nemacheilidae)

by

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Abstract

Climate change is having a major impact on species distribution and habitat loss, especially for species with restricted ranges. The genus *Seminemacheilus* is endemic to Türkiye and includes six species. This study investigated the current distribution of the genus *Seminemacheilus* and its possible distribution in 2050 and 2070 using the Wallace platform, a Maxent modeling method. Simulations of future projections indicated that bioclimatically suitable habitats of *Seminemacheilus* spp. will be limited in 2050 and nearly extinct in 2070. The model is primarily affected by temperature and precipitation, which are directly associated with the phenomenon of global warming. It has been established that conservation strategies must be developed to protect the species of the genus and avoid habitat deterioration.

Key words: Ecological niche model, global climate change, ichthyogeography, Maxent, *Seminemacheilus*, Wallace

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1. Introduction

Due to its favorable geographic location, combined with the complex topography and geomorphology of Anatolia, Türkiye plays a crucial role in maintaining global biodiversity. The aforementioned geographic features play a key role in particular in supporting a diverse array of habitats and species. The global biodiversity hotspot map provides valuable insights into Türkiye's vital importance to worldwide conservation (Norozii et al. 2019; KBA 2023). Due to its geographic location and the presence of diverse habitats, the country also exhibits a notable abundance of freshwater fish species, exceeding other countries within its geographic region in terms of species diversity (Çiçek et al. 2023; Saad et al. 2023; Froese and Pauly 2023). Based on the recent data, Türkiye is home to a total of 427 species of freshwater fish, with about 50% of these species categorized as endemic (Çiçek et al. 2018; Çiçek et al. 2020; Çiçek et al. 2023). One of the constituents of this diverse ichthyofauna is the endemic genus *Seminemacheilus* Banarescu & Nalbant, 1995. The genus *Seminemacheilus* includes six species, viz. *Seminemacheilus lendlii* Hanko, 1925, *Seminemacheilus ispartensis* Erk'akan, Nalbant & Özeren, 2007, *Seminemacheilus ahmeti* Sungur, Jalili, Eagderi & Çiçek, 2018; *Seminemacheilus dursunavsari* Çiçek, 2020; *Seminemacheilus ekmekciae* Yoğurtçuoğlu, Kaya, Geiger & Freyhof, 2020 and *Seminemacheilus attalicus* Yoğurtçuoğlu, Kaya, Geiger & Freyhof, 2020, all being endemic to the inland waters of Türkiye (Sungur et al. 2018; Çiçek 2020; Yoğurtçuoğlu et al. 2020; Fricke et al. 2023; van der Laan 2022). The first studies on the genus started with the transfer of the species *Nemacheilus lendlii* Hanko, 1925 to this genus by Banarescu and Nalbant (1995), with the first description of the new genus as *Seminemacheilus*. No new records were published for many years, after which *S. ispartensis* was described as a new species in 2007 (Erk'akan et al. 2007). In 2018, *S. ahmeti* was described from the Sultan Marshes as a new species (Sungur et al. 2018). Then, *S. dursunavsari*, *S. attalicus* and *S. ekmekciae* were identified as new species and the number of species belonging to the genus increased to six (Çiçek 2020; Yoğurtçuoğlu et al. 2020). Currently, this genus includes six species: *S. lendlii, S. ispartensis, S. ahmeti, S. dursunavsari, S. ekmekciae* and *S. attalicus*, which occur in Central Anatolia, the Sakarya River basin, Eğirdir and Salda lakes, the Sultan Marshes, the Göksu River basin, the Salt Lake Basin and the Antalya Basin (Kırkgöz drainage), respectively (Fricke et al. 2023; van der Laan 2022). The taxonomic history shows that the genus *Seminemacheilus* includes several species that have been documented in recent years. However, there is a dearth of comprehensive research on these species, with limited studies focusing primarily on their descriptions and geographic distribution. Only two of these species, *S. lendlii* and *S. ispartensis*, have been classified as Vulnerable (VU) by the International Union for Conservation of Nature (IUCN), while the remaining four species are currently assigned no classification (IUCN 2023).

The geographic distribution of species is a function of biotic, abiotic and movement factors, of which climate is a major factor determining the distribution of species (Fei et al. 2012; Engler et al. 2013; Esmaeili et al. 2018). Climate is subject to temporal changes as a result of alterations in external factors and processes, as well as its inherent internal dynamics. Before the advent of human civilization, geographic features of the Earth underwent numerous changes. Therefore, significant climatic changes occurred at different intervals, contingent upon the disruption of the inherent balance between the constituents of our planet (Öztürk 2002). Freshwater fauna around the world face serious threats due to many disturbances, such as land use changes, water use policies, urban expansion, wetland depletion, illegal hunting, introduction of non-native species, and especially the impact of climate change (Dudgeon et al. 2006; Heino et al. 2009; Anonym 2023; Comte 2013; Bizama et al. 2023). Nonetheless, freshwater fish tend to occupy more limited latitudinal ranges, resulting in faunal levels corresponding more closely to experienced temperatures, and species with restricted ranges are highly vulnerable to climate change (Bizama et al. 2023). On the other hand, taxa with a wider geographic distribution may exhibit reduced vulnerability and potentially increased adaptive capacity in response to global warming. In this respect, species belonging to *Seminemacheilus*, which have a sensitive ecological tolerance level will also be affected by climate change. The ability to anticipate the impact of climate change on species is of utmost importance for habitat conservation and species persistence, particularly for species inhabiting shallow water bodies within fragmented habitats. Aksu (2021) pointed out that there will be a significant decline in habitats suitable for *S. lendlii* by 2070.

Species distribution models (SDMs) are numerical tools that combine observations of species occurrence or abundance with environmental estimates and have been employed to forecast future distribution strategies and can be used as a first step to understand changes in species distribution under future environmental scenarios (Elith & Leathwick 2009; Bizama et al. 2023). The main objective of this research is to identify current climatically appropriate habitats for the species and assess potential changes in climatically suitable habitats for the genus using climate projections for 2050 and 2070.

2. Materials and methods

2.1. Occurrence data and bioclimatic variables

In the current study, we analyzed and mapped correlations between 19 bioclimatic variables (Bio 1–19) and occurrence data to assess species distribution models (SDMs) of the genus. The materials for this study (a total of 27 localities) were derived from the fieldwork conducted by the authors between 2014 and 2020 (deposited in Nevsehir Hacı Bektas Veli University Ichthyology Collection, NHVUIC), the GBIF database and available published data (Bănărescu & Nalbant 1995; Erkakan et al. 2007; Yoğurtçuoğlu 2020; GBIF 2022). The distribution map of *Seminemacheilus* species showing the above-mentioned localities (Fig. 1) was generated using ArcGIS 10.7 (Redlands 2011). Bioclimatic variables were obtained by directly accessing the WorldClim database (specifically Bio 1–19) using Wallace software (Fick & Hijmans 2017). Bioclimatic data with 2.5 arcmin (~5 km^2) resolution were loaded from the WorldClim Bioclims module (Fick & Hijmans 2017).

2.2. Modeling methodology

The construction of the SDMs was carried out using the Wallace platform and the Maxent approach. Wallace is a user-friendly and adaptable software tool that uses a graphical user interface to perform species distribution modeling by using a range of R packages (Kass et al. 2018; Gür 2019). The occurrence data were spatially thinned to 24 with a distance of 5 km. Random background points were sampled (n = 100000) with a 10 degree (~1110 km) buffer area. The block method (k = 4) was used to select records for model development and training. Linear, quadratic, hinge and product feature classes, as well as 10 regularization multipliers were used to regulate the model complexity. In this way, five model combinations were generated for these feature classes and a total of fifty distinct models were obtained. In evaluating the results of the analysis, the model that best separated the presence data from the background data was selected based on the area under the curve (AUC) value supporting that model (Phillips et al. 2006; Baldwin 2009; Elith et al. 2011). The response curves of each variable were analyzed with the purpose of interpreting the selected models. On the basis of these curves, climatic parameters affecting the bioclimatic suitability of the species were assessed and model estimations were plotted (cloglog/no threshold). Changes in the climatic niche of the genus with the

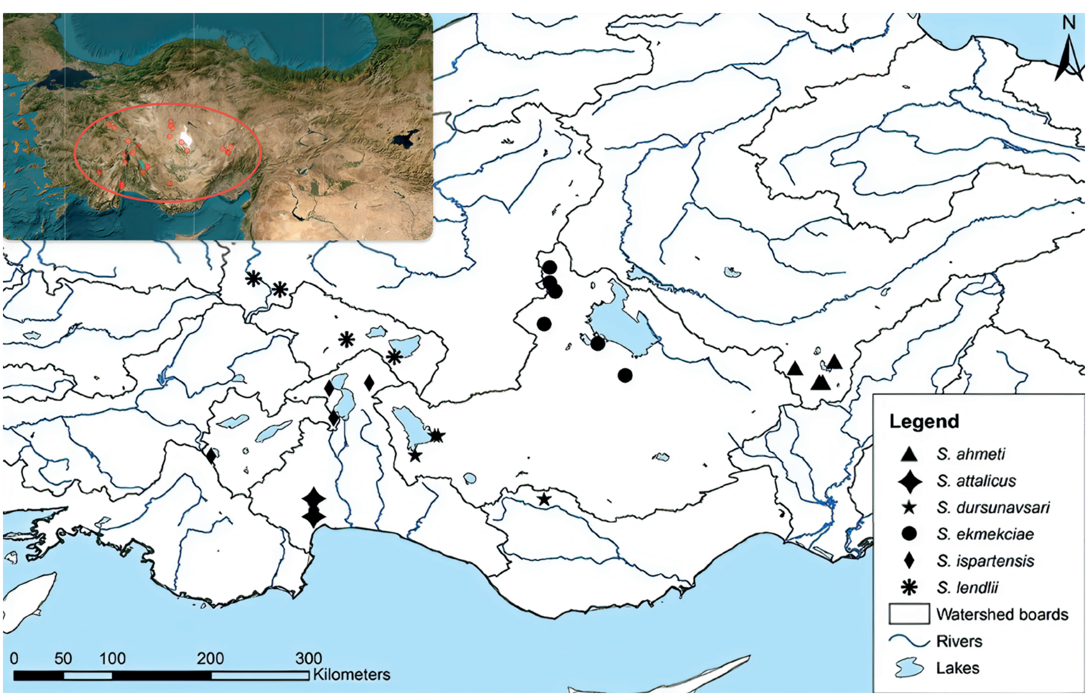

Figure 1
Distribution map of *Seminemacheilus* species.

future Global Climatic Model (GCM), Community Climate System Model version 4 (CCSM4) and Representative Concentration Pathway (RCP) 8.5 were used to estimate habitat suitability for 2050 and 2070.

3. Results

The study assessed the relationship between the occurrence of the genus *Seminemacheilus* and bioclimatic variables. Predicted distribution maps were generated for 2050 and 2070. The distribution of *Seminemacheilus* species in Türkiye is shown in Figure 1 and potential distribution localities in Figure 3a.

The SDMs obtained for the genus *Seminemacheilus* showed relatively good performance with AUC values of 0.984 (SD = 0.001). In the bioclimatic suitability maps of the model predictions, appropriate areas for the distribution of these species ranged from 0 (lowest probability) to 1 (highest probability; Fig. 3). The regions closest to 1 indicate a high probability of occurrence of the species in their identified habitats and adjacent areas, whereas the regions closest to 0 indicate a low probability of species occurrence. Likely distribution patterns of *Seminemacheilus* species were predicted for 2050 and 2070 using the CCSM4 global circulation model and the RCP 8.5 representative concentration scenario presented in Figures 3b, c.

Annual mean temperature, mean diurnal range, temperature seasonality, annual temperature range, mean temperature of the wettest quarter, mean temperature of the warmest quarter, mean temperature of the coldest quarter, annual precipitation, precipitation of the wettest month, precipitation of the driest month, precipitation of the wettest quarter, precipitation of the driest quarter, precipitation of the warmest quarter and precipitation of the coldest quarter are factors that affect the bioclimatic suitability of the genus *Seminemacheilus*. Factors that do not affect the response curves include: isothermality, maximum temperature of the warmest month, minimum temperature of the coldest month, mean temperature of the driest quarter, and precipitation seasonality (Table 1, Fig. 2).

S. ahmeti is a species that was identified in the Sultan Marshes, an endorheic subbasin located in the Kayseri Province of the Central Anatolia Region, Türkiye. The species is only found in small streams of the Soysallı and Gurba springs, which contribute water flow to the Sultan Marshes (Çiçek & Sungur 2020; Sungur et al. 2023). *S. attalicus* was identified in the Kırkgöz drainages in the Antalya Province, located in southern Anatolia, Türkiye. It is worth noting that this particular geographic region represents the exclusive habitat where this species has been recorded. *S. dursunavsari* is a species that was discovered in the catchment area of the Göksu River, located in the Eastern Mediterranean basin in the Konya Province. The species is known to be dispersed throughout the basin, as well as in the Beyşehir watersheds. *S. ekmekciae* is a species that was identified in the Insuyu region of Cihanbeyli, located in the Konya Province. The species is found in the Salt Lake Basin, which is a subbasin of the Konya Closed Basin. In addition, it is widely distributed in the endorheic Salt Lake Basin. Species that were listed earlier (before 2018) include *S. lendlii* and *S. ispartensis*. The species *S. lendlii* has been documented to originate from the Eskişehir Province in western Anatolia. It is currently found in the Upper Sakarya Basin, as well as in the basins of the endorheic lakes Akşehir and Eber. The species under consideration is the first species within the genus, documented by Hanko in 1925 and identified as *Nemacheilus lendlii*. The species *S. ispartensis* is found in the basins of Lake Eğirdir and Lake Salda, located in the province of Isparta. The species was initially described by Erkakan et al. (2007) based on specimens collected from the Isparta creek (Hanko 1925; Erkakan et al. 2007; Sungur et al. 2018; Çiçek et al. 2020; Yoğurtçuoğlu et al. 2020; Aksu 2021; Sungur et al. 2023; Fricke et al. 2023).

As indicated by the type localities and distribution areas, the genus under consideration occurs mainly in Anatolia. The present potential species distribution

Table 1

Bioclimatic variables.

Abbreviation	Bioclimatic variables
Bio1	Annual Mean Temperature*
Bio2	Mean Diurnal Range*
Bio3	Isothermality
Bio4	Temperature Seasonality*
Bio5	Max Temperature of Warmest Month
Bio6	Min. Temperature of Coldest Month
Bio7	Temperature Annual Range*
Bio8	Mean Temperature of Wettest Quarter*
Bio9	Mean Temperature of Driest Quarter
Bio10	Mean Temperature of Warmest Quarter*
Bio11	Mean Temperature of Coldest Quarter*
Bio12	Annual Precipitation*
Bio13	Precipitation of Wettest Month*
Bio14	Precipitation of Driest Month*
Bio15	Precipitation Seasonality
Bio16	Precipitation of Wettest Quarter*
Bio17	Precipitation of Driest Quarter*
Bio18	Precipitation of Warmest Quarter*
Bio19	Precipitation of Coldest Quarter*

*variables that affect the model

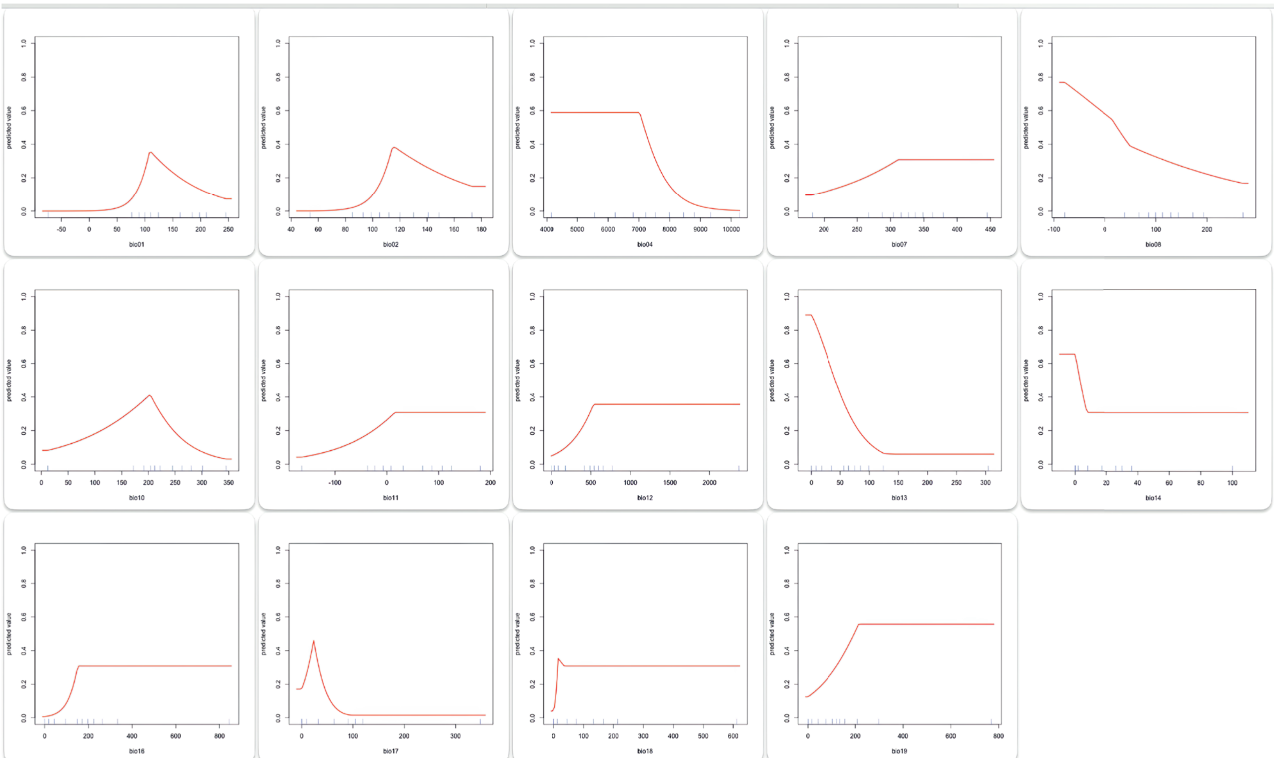

Figure 2

Predicted bioclimatic response curves.

model (SDM) suggests that the most suitable localities for this genus are concentrated in the Konya endorheic basins and the western Mediterranean basins (Fig. 3a). Based on the species distribution modeling conducted for 2050, it can be seen that the possible appropriate habitats are characterized by small, fragmented areas in the Konya Closed Basin, the Sakarya Basin, the Central Mediterranean Basin, and the upper section of the Kızılırmak Basin, and the genus will experience a significant loss of its preferred habitats in the Konya endorheic and Mediterranean basins, along with other regions, by 2050. However, it appears that by 2070 there will be no definitive geographic region that can be considered the most suitable habitat for the genus, with a few exceptions. All projected locations exhibit lower levels of suitability (Fig. 3b,c).

4. Discussion

According to the obtained species distribution models, the area of suitable habitat for the genus *Seminemacheilus* will be considerably reduced by 2050 and will almost completely disappear by 2070 (Fig. 3). They indicate that the climatic factors with the greatest impact on the distribution of this species are temperature and precipitation. Indeed, the two most important consequences of global climate change are rising temperatures and changes in precipitation patterns. Global warming has a direct impact on precipitation. Increased warming leads to more evaporation and thus surface drying, thereby increasing the intensity and duration of drought. However, the capacity of the air to hold water increases by about 7% per 1°C warming, which leads to increased water vapor in the atmosphere (Giannakopoulos et al. 2009; Trenberth 2011). Changes in rainfall patterns can cause these environments to become completely dry at some times and subject to flash flooding at other times. The risk of runoff and flooding increases in early spring because as temperatures rise, more precipitation occurs in the form of rain rather than snow, and snow melts earlier. The risk of drought, on the other hand, increases in summer (Giannakopoulos et al. 2009; Trenberth 2011). Consequently, there would be a significant threat to the survival of *Seminemacheilus* species dispersed in unconnected wetlands. Global climate change is causing significant changes in temperature and precipitation patterns, resulting in some water sources drying up (Aksu 2021). According to Aksu (2021), a SDM of *S. lendlii* indicates that there will be a significant

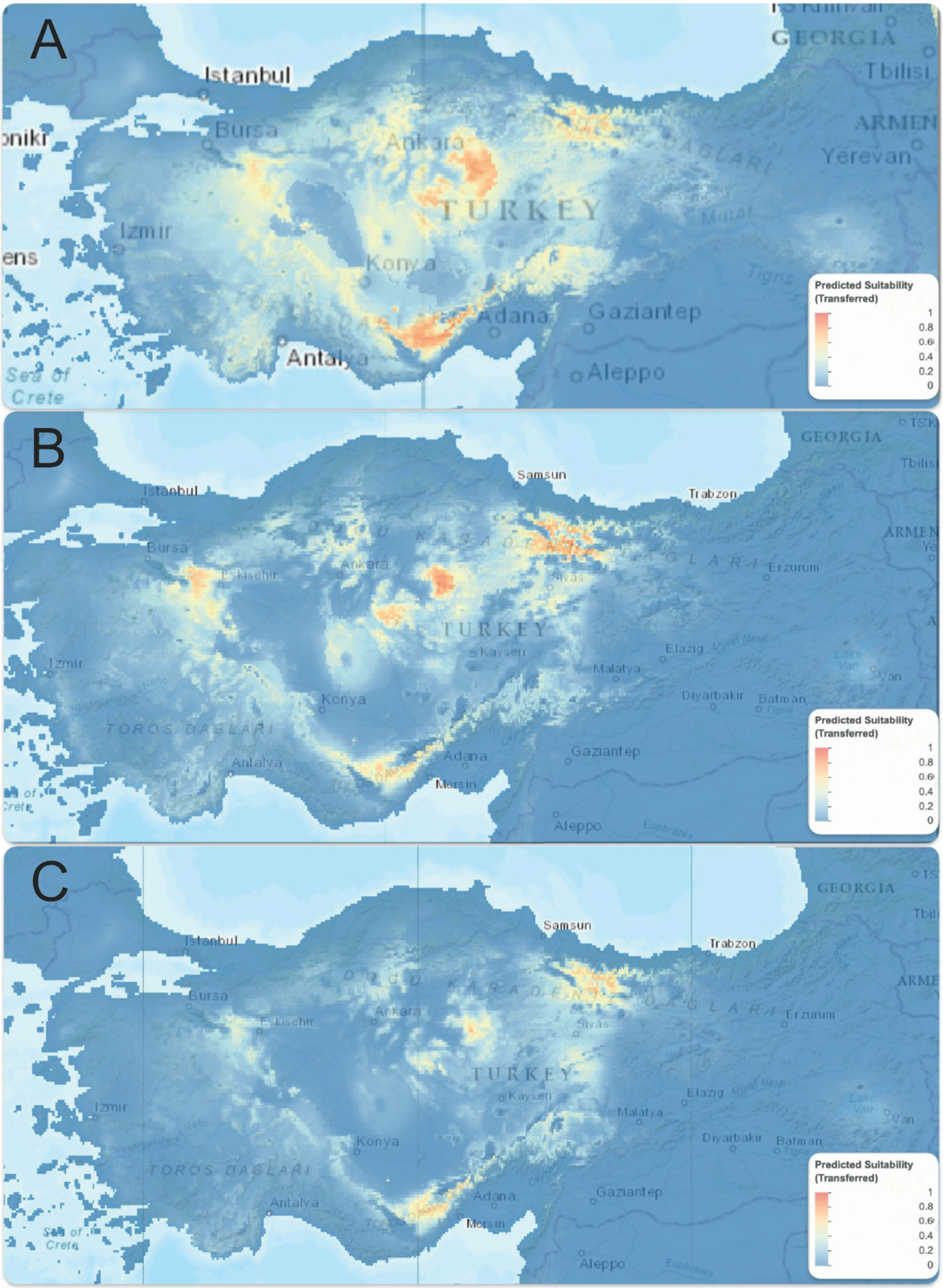

Figure 3

a) Predicted suitability; b) 2050 projection; c) 2070 projection maps of *Seminemacheilus*.

decline in suitable habitats by 2070. The results of this study are consistent with previous studies, suggesting that the availability of appropriate habitats for the species is expected to be severely reduced in the future.

The genus *Seminemacheilus* is distributed in disconnected habitats of the Sultan Marshes (*S. ahmeti*), the Salt Lake Basin (*S. ekmekciae*), the Antalya Basin (*S. attalicus*), the Sakarya Basin (*S. lendlii*), Beyşehir, Eğirdir, Eber, Akşehir lake basins (*S. ispartensis*), and the Göksu Basin (*S. dursunavsari*) (Çiçek 2020; Yoğurtçuoğlu et al. 2020; Fricke et al. 2023; Fig. 1). According to Aksu (2021), Lake Eber and Lake Akşehir have reached the point of losing a significant amount of their water, and the Sakarya Basin is under pressure from pollution. While these regions are critical habitats for *S. lendlii*, some of the suitable habitats suggested in the modeling are also located in these basins. The same phenomenon was also documented in the field studies carried out in the Kırkgöz drainages and the Sultan Marches in 2022 and 2023. Therefore, in addition to the predicted effects of climate change and desiccation, anthropogenic pollution was also identified in these areas, which include the distribution areas of four of these species.

The fact that these species inhabit disconnected endorheic environments is a factor restricting their dispersal. Also limiting the dispersal of these species is their low ecological tolerance and geographic barriers. All species of the genus prefer slow-flowing and/or shallow, stagnant bodies of water with extensive vegetation and sandy bottoms and are highly sensitive to changes in these habitats (Freyhof 2014; Sungur et al. 2018). The overall effects of climate change on freshwater systems is likely to be increased water temperature, reduced dissolved oxygen levels, and increased toxicity of pollutants. In lotic systems, altered hydrological regimes and increased groundwater temperatures may affect the quality of fish habitats. In lentic systems, eutrophication may be exacerbated or offset, and stratification will likely become more pronounced and stronger. This may change food webs and habitat availability and quality (Fricke et al. 2007). Comparing bioclimatically appropriate habitats in 2050 to the current distribution pattern of the species, the model predicts a shift toward the northwestern region of the Sakarya Basin and north-central Anatolia. Suitable ecosystems can be identified through modeling studies to be carried out, taking the physicochemical parameters of the water into account, and species can be transferred to ecosystems where there will be no niche conflicts based on an assessment of the suitability of the ichthyofauna.

Ecological niche modeling is a popular method for studying the distribution patterns of species, but it has also been used to infer the processes involved in their distribution (Donald et al. 2001; Maestre 2006). This approach has shown that the survival of aquatic species in a region is partly determined by physicochemical factors such as water depth, hydraulic regime, water temperature, dissolved oxygen concentration, pH, and salinity. Therefore, determining the distribution of fish populations according to physicochemical and hydrological characteristics and habitat suitability is essential for species conservation.

According to the results of this study, habitats considered favorable for these species, currently limited to a few scattered locations in fragmented ecosystems, are expected to be significantly reduced. Consequently, the populations of these species are expected to experience a substantial decline, possibly leading to their extinction, due to the aforementioned risks. Habitat reduction has a direct impact on population size, leading to a decline in the number of individuals. The aforementioned predictions and data have been documented to indicate a significant concern for *S. lendlii* (Aksu 2021) and *S. ahmeti* (Çiçek & Sungur 2020; Sungur et al. 2023), as well as other species in this genus. While the IUCN conservation status of *S. lendlii* and *S. ispartensis* has been determined as VU (Vulnerable), other species have not yet been assessed (IUCN 2023). Therefore, it is imperative to implement the IUCN classification for these species and develop species conservation action plans. In research laboratories, it is important to engage in the reproduction of these animals and ensure the perpetuation of the species through practices such as relocation and immunization to appropriate habitats, while considering their cohabitation.

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Conflict of Interest

The author declares no conflict of interest.

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