Caspian Journal of Environmental Sciences
Online ISSN: 1735-3866
Print ISSN: 1735-3033

Predicting impacts of climate change on the distribution of *Luciobarbus brachycephalus* (Kessler, 1872) in the southern part of the Caspian Sea basin

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ABSTRACT
Iran is one of the most important biodiversity areas in the world. However, currently, most freshwater ecosystem fish species in this country face serious threats due to human activities. In addition to these threats, climate change is also a double threat that may accelerate extinction or decrease the population size of species. *Luciobarbus brachycephalus* is one of the native and valuable fishery species in the southern Caspian Sea Basin, which is categorized as endangered in the latest list provided by the International Union for Conservation of Nature (IUCN). In this study, the distribution of the aforementioned species in two optimistic and pessimistic scenarios (RCP 2.6, RCP 8.5) for 2050 and 2080 was predicted using the Maxent model. The results showed that the performance of the model in predicting species distribution based on the Area Under the Curve (AUC) criterion was excellent. Based on the predictions, it was found that this species will likely face a decrease in habitat suitability in the future in all optimistic and pessimistic scenarios for 2050 and 2080. The range of changes in all the mentioned situations is negative (i.e., the percentage of habitat suitability decrease is greater than its increase). Therefore, it is suggested that managers and decision-makers prioritize the protection of this economically important species to ensure that its population does not become completely extinct in the future. In addition, such a study of other species in the Iran regions can effectively help protect the valuable biodiversity of this area against various threats, especially climate change.

Keywords: Biodiversity, Climate change, Species distribution modeling, Maxent, Conservation.

INTRODUCTION
Today, the phenomenon of climate change is one of the most important issues, and human activities affecting the global climate system are noteworthy (Bellard *et al*. 2012; Raihan 2023; Rawat *et al*. 2024). This phenomenon impacts all natural ecosystems on both global and local scales, as is observed in all regions of the world. Although increases in extreme weather and temperature events will amplify water quality fluctuations and hydrological stress (Nowicki *et al*. 2019; Furtak *et al*. 2023; You *et al*. 2023; Sabater *et al*. 2023; Wollschläger *et al*. 2024), resolving the impact of climate change on fish populations is critical, as climate change and global distribution affect many ecosystems. Various factors may influence different processes at different levels of biological organization (Szymonowicz *et al*. 2020; LaRue *et al*. 2023). Owing to destructive human activities, global warming has led to a multitude of successive environmental effects, including rising sea levels, changing weather patterns, frequent and severe natural disasters, and disruption of ecosystems worldwide (Upadhyay 2020; Szymonowicz *et al*. 2020; Rajak 2021; Chen *et al*. 2023; Saberi-Pirooz *et al*. 2024). Climate change and its interaction with other drivers, such as human development, pollution, and invasive species, have made forecasting

and management challenging (Wudu *et al*. 2023; Sun *et al*. 2023; Khattak *et al*. 2024). Due to its unique geographical location and special topographical features, such as the large area and the presence of two mountain ranges, Alborz and Zagros, Iran has high species diversity in climate and natural ecosystems. However, more than 80% of the area of Iran is covered by arid and semi-arid climates. The average annual rainfall in Iran is approximately 250 mm (Asakereh *et al*. 2023). Despite this, due to topographic features, multiple watersheds (19 main watersheds) with a network of rivers and waterways in Iran have a high level of ground biodiversity protection (Karimi *et al*. 2020; Pirali Zefrehei *et al*. 2023). Multiple factors, such as changes in water quality, hydrology, morphology, land use, and the introduction of non-indigenous species, along with overfishing, threaten the diversity of the country's aquatic ecosystems (Mostafavi *et al*. 2015). Fish have complex life cycles, comprising several distinct life-history stages (eggs, larvae, juveniles, and adults), each of which may be affected differently by climate change (Feely *et al*. 2004; Bellard *et al*. 2012; Sharma *et al*. 2023). The general effects of climate change on freshwater ecosystems include an increase in water temperature, a decrease in dissolved oxygen, and an increase in pollutant toxicity. These effects are particularly impactful on aquatic species, especially fish, due to the influence of fish physiology and water temperature (Ficke *et al*. 2007; Pörtner *et al*. 2010; Alfonso *et al*. 2021; Soomro *et al*. 2023; Mangi *et al*. 2024).

Today, one of the most important methods for investigating issues and interpreting existing data is the use of modeling methods, particularly statistical ones. This approach helps to understand the functions and complexities of the real world and its existing forms. One of the most significant methods is species distribution modeling (SDM), which serves as a practical tool for examining the relationship between geographic distribution data and the environmental conditions of species (Elith & Leathwick 2009; Putri *et al*. 2022). *L. brachycephalus* is one of the species in the Caspian basin that holds economic and sporting value (Jouladeh-Roudbar *et al*. 2020). It usually prefers warm, deep, and calm waters with a pebble or sandy bed. Large specimens of this fish feed on smaller fish and frogs (Keivany *et al*. 2016), while small specimens feed on crustaceans, insects, and mollusks (Coad 2021). *L. brachycephalus* usually has a medium regeneration ability, and its minimum doubling time is 4.5 to 14 years (Keivany *et al*. 2016). According to the reports presented, *L. brachycephalus* is in the VU (vulnerable) category (Keivany *et al*. 2016; Jouladeh-Roudbar *et al*. 2020). Additionally, this species depends on river ecosystems for its survival and migrates from the east to the west of the Caspian basin in our country for spawning (Keivany *et al*. 2016; Coad 2021).

Considering that the species diversity of the rivers in the southern basin of the Caspian Sea is greater than in other basins, and that they contain economically important fish species, their populations are declining in their original habitats primarily due to human activities and various threats. Therefore, the present study was conducted to investigate the effect of climate change on the distribution of big carp (*L. brachycephalus*) in the rivers of the southern basin of the Caspian Sea under different climate change scenarios for the years 2050 and 2080.

MATERIALS AND METHODS

Study area

The area studied in this research was Iran, with the geographical location of the rivers in the southern basin of the Caspian Sea. Iran is situated at the meeting point of three bioregions including Palearctic, Ethiopian and Oriental, which is why it has unique habitats and species in the Middle East (Kafash *et al*. 2020). In this study, the presence-absence technique was employed for modeling, as illustrated in (Fig. 1):

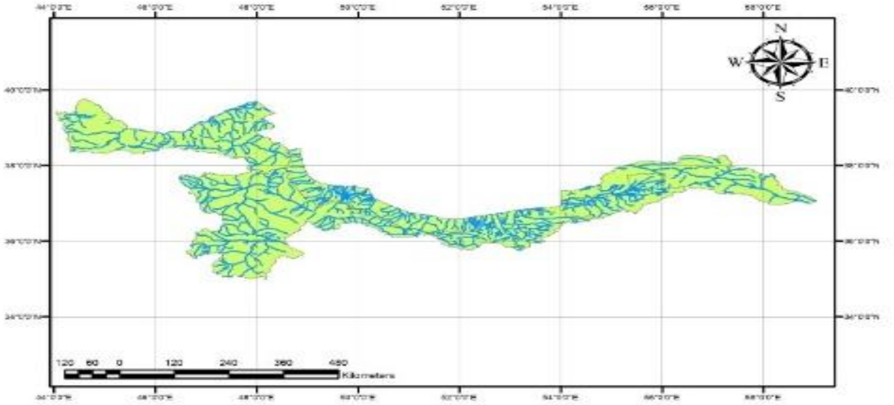

Fig. 1. Layer of the Iranian rivers in the southern basin of the Caspian Sea (Arc GIS ver. 10.8).

The collection of environmental and climatic data used for species modeling, including residential and climatic data, was obtained from reliable foreign sites such as www.worldclim.org and domestic organizations (natural resources and environment). Nine variables were considered as primary variables: maximum river width (Max-Width), elevation (Elevation), slope (Slope), flow accumulation (Flow Accumulation), average temperature difference between the coldest and hottest months of the year (temperature range; Ave-Trange), average mean temperature (Ave-Tmean), average minimum temperature (Tmin), average maximum temperature (Tmax), and average precipitation (Ave-Precipitation). After performing the Spearman correlation test, if two variables showed a correlation above 75%, one was selected based on expert opinion and the ecological needs of the species (Mostafavi *et al*. 2014; Makki *et al*. 2023).

Table 1: A quantitative and qualitative classification of model performance based on the AUC index

Model performance	Value AUC
Very poor	0.6-0.7
poor	0.7-0.8
Good	0.8-0.9
Excellent	0.9-1

Table 2: How to measure changes in species distribution range.

parameter	Gain (%)	Loss (%)	Range of change in distribution
Formula	Gain/NC * 100	Loss/NC *100	Loss (%) _Gain (%)

Table 3. Environmental variables were used in this study.

Category	**Variable**	**Source**
Bioclimatic variables	BIO1 = Annual Mean Temperature (◦C) BIO7 = Temperature Annual Range (◦C) BIO12 = Annual Precipitation (mm)	www.worldclim.org
Topographic variables	Slope (Degree)	www.isric.org / www.worldgrids.org
Global hydrography datasets	Flow Accumulation Upstream Drainage Area	http://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_Hydro/

RESULTS AND DISCUSSION

Among the nine primary variables, the following five were selected for modeling after testing: temperature, annual range, annual precipitation, slope, and flow accumulation Fig. 2.

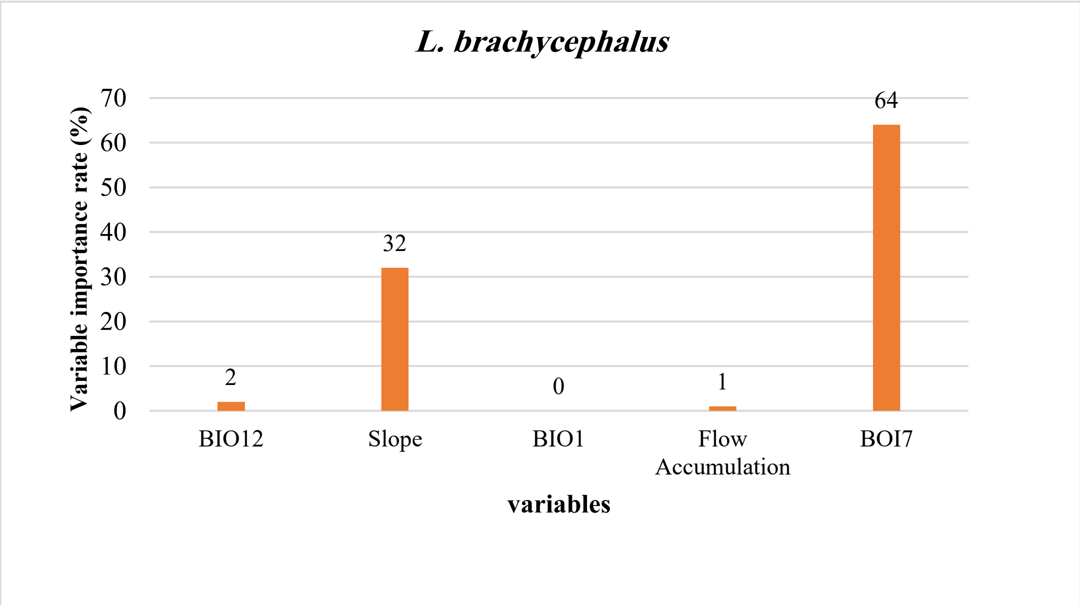

Fig. 2. Variables importance for distribution of *L. brachycephalus*.

Model performance. According to the results of the Maxnet model using the AUC index, the performance of the model for the studied species, *L. brachycephalus*, was excellent (AUC = 0.927; Fig. 3).

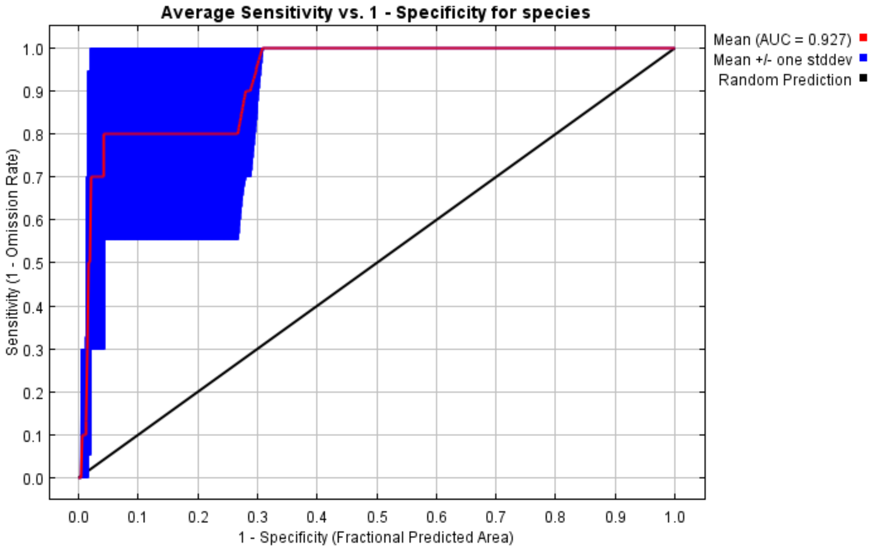

Fig. 3. Receiver operating characteristic (ROC) curve and AUC index.

Prediction of species distribution. Based on the modeled predictions, it was found that this species will likely face a decrease in habitat desirability in the future across all optimistic and pessimistic scenarios for 2050 and 2080. In other words, the range of changes in all the mentioned states is negative (i.e., the percentage of habitat desirability reduction is greater than its increase; Table 4).

Table 4. Percentage of gain, loss, and range change of species under scenarios for 2050 and 2080.

species	Climate scenarios	RCP2.6		RCP8.5	
	Time period	2050	2080	2050	2080
L.brachycephalus	Gain (%)	+19.77	+22.31	+16.61	+21.86
	Loss (%)	-24.13	-30.18	-24.73	-33.39
	Range of change in distribution	-4.36	-7.87	-8.12	-11.53

The modeling results of the present study showed that with climate changes in different optimistic and pessimistic scenarios of various years, climate change, as one of the biggest environmental challenges, now affects the habitat suitability and distribution of *L. brachycephalus*. If we do not pay enough attention to the issue of climate and the consequences of its change, humanity may face disasters in the coming years. Currently, due to declining species numbers, Planet Earth is in the midst of a biodiversity crisis that is particularly severe in freshwater ecosystems (Blowes *et al*. 2019; Shivanna 2020; Su *et al*. 2023). Therefore, it is necessary to properly manage all the obstacles and problems facing this species of native value, as well as to facilitate the migration and movement of freshwater fish in rivers with appropriate protection strategies in each region (Mustafavi *et al*. 2022).

The most important part of species distribution modeling is to select and use appropriate environmental variables that describe the geographical and biological conditions of the species and accurately predict its distribution range. Considering that the identification of all the variables and factors affecting the features of the species' position in the modeling is hindered by the lack of ecological knowledge about the studied species, the insufficient understanding of all dimensions of the species' niche, and the limitations in the availability and use of all variables in the form of information layers, it is not feasible (Bisson *et al*. 2008; Logs *et al*. 2012). Freshwater fish are thermogenic animals and are particularly sensitive to temperature. Fluctuations in temperature affect the metabolism, breeding, growth, and development of fish (Burt *et al*. 2011; Volkoff *et al*. 2020; Liu *et al*. 2023). In addition, average air temperature has been widely reported as an important variable affecting fish distribution (Bisson *et al*. 2008; Pörtner *et al*. 2010; Mostafavi *et al*. 2014, 2015; Baudron *et al*. 2020; Makki *et al*. 2023; Farzi *et al*. 2024), which is in accordance with the results of this study. The slope variable, in general, depends on the ecology of fish, which in this study was of high importance for the species examined and is consistent with previous researches (Filipe *et al*. 2013; Radinger *et al*. 2014; Mostafavi *et al*. 2014; Cano-Barbacil *et al*. 2020;

Verberk *et al.* 2022). Comparing the results of the studied species complex distribution modeling with existing reports (Mostafavi *et al*. 2014; Khaefi *et al*. 2017a) shows that the members of the *Barbus* species were predicted not only in the Caspian Sea, Urmia, Namak, and Tigris basins, but also in the Hari River basin and Upper Tigris River drainage. Moreover, in the same recorded basins, some new sites were identified. Among the two main reasons for the difference in results, the sampling methods employed by researchers may not be comprehensive, as almost every year new species are described from distant and mountainous areas of Iran (Khaifi *et al*. 2017a; Esmaili *et al*. 2018). Limiting factors can also be attributed to the distribution of freshwater fish species. Although the distribution of a species can be considered based on the relationship between environmental conditions and intrinsic characteristics of the species in terms of its potential distribution, various natural and artificial factors have restricted the actual distribution of species (Sexton *et al*. 2009; Reddy *et al*. 2021; Carlson *et al*. 2022; El-Naggar *et al*. 2022; Joly *et al*. 2024; Farzi *et al*. 2024). Given that the river network is the only way to distribute fish species, one of the main natural limiting factors in freshwater ecosystems is the basin border, which restricts the movement of species between basins (Schmutz *et al.* 2000; Pont *et al.* 2005). While the habitat suitability for a species may extend beyond its original watershed, the distribution of species within the watershed may encounter various barriers, especially artificial constructions such as dams, which result in the limited distribution of a species in the watershed. Species distribution can also be influenced by biological interactions, where the importance of certain traits, such as competition and predation, is significant (Araujo and New 2007; Wisz *et al*. 2013; Akesson *et al*. 2021; Ponti *et al*. 2023).

Based on the findings of the present research, under the influence of climate change, the distribution range of the fish will decrease significantly in the future. In other words, the range of desirable habitats for this fish will be limited. By observing the obtained modeling maps, it is clear that in the Caspian watershed, the amount of lost sites for this fish will be much greater than the gained sites. In other words, the fish species will lose much of its habitat without a replacement being created. Considering that many studies have been conducted on the aquatic population and diversity in relation to climate, the high value of this fish has been proven by researchers (Heidari *et al*. 2019; Nik Mehr *et al*. 2020; Tabsinejad *et al*. 2023). Water temperature changes are one of the most important consequences of climate change (Markovic *et al*. 2014; Woolway *et al*. 2020; Salimi *et al.* 2021; Richardson *et al*. 2024; Wang *et al*. 2024; Farzi *et al*. 2024). Water temperature, by changing other environmental parameters and disrupting the physiological and ecological processes of fish, will greatly affect them (Schmutz *et al*. 2018; Mustafavi *et al*. 2021). As a result, the species, in case of incompatibility with the established conditions, will leave its current location to continue its life and seek a new favorable habitat (Polterbauer *et al*. 2018; Makki *et al*. 2023; Farzi *et al*. 2024).

Several studies conducted on fish species in the field of modeling and climate change have shown different responses to climate effects. Consistent with the present study, Farzi *et al*. worked on one of the native and valuable fishery species of the southern Caspian Sea basin, the large barbel, *Luciobarbus capito*, which is listed as Vulnerable (VU) in the latest list of the International Union for Conservation of Nature (IUCN). In this study, the distribution of the species was predicted using two approaches: optimistic (RCP2.6) and pessimistic (RCP8.5) for the years 2050 and 2080, employing the maximum entropy (MaxEnt) model. The results showed that the model's performance in predicting the distribution of the species, based on the AUC evaluation criterion, was excellent (0.934). Based on the modeled predictions, it was determined that this species will likely face a decrease in habitat suitability in the future under both optimistic and pessimistic scenarios for the years 2050 and 2080 (Farzi *et al*. 2024). Also, Ahmadi and Mostafavi predicted the climatic effects on the distribution of benny, *Mesopotamichthys sharpeyi*. They concluded that it faces climate change in 2050 and 2080 under both optimistic and pessimistic scenarios, with a decrease in the range of distribution of these species. Makki *et al*. (2021) modeled and investigated the effects of climate change on the distribution of *Garra rufa*. The results of this research showed that in 2050 and 2080, the distribution of the species will experience an increasing and decreasing trend in two optimistic and pessimistic modes, however, the rate of decrease in distribution in the study area is much higher. Regarding the increase in distribution, Darabi *et al*. (2020) concluded that in the optimistic scenarios of 2050 and 2080, the range of distribution of Fars botak, *Cyprinion tenuiradius* will decrease slightly, while the range of its distribution will increase slightly in the pessimistic scenario of 2050. In addition, this research showed that in the pessimistic scenario of 2080, the favorable habitats of Fars botak will increase significantly. In 2023, Tebsinejad *et al.* modeled the distribution of kutum, *Rutilus kutum* under the influence of climate change over the next 30 and 60 years. They reported that the distribution of this species will decrease significantly in all years and under both optimistic and pessimistic climatic conditions. These researchers declared that the annual temperature range is the most important environmental variable affecting the distribution of this native species in the coming years (Tebsinejad *et al*. 2023). Hijazi *et al.* (2023), evaluated the distribution range of *Capoeta damascina* species under climatic conditions (optimistic and pessimistic factors), predicting that the distribution range of this fish will decrease significantly in the following years. Several factors will be involved in increasing and decreasing the distribution range of fish in the coming years, the most important is the inherent resilience of the species against changing environmental conditions (Makki *et al*. 2023).

In another study conducted by Yousefi *et al.* in 2020, the researchers planned to use native freshwater fish as a sample of their ecosystem to identify high-priority rivers for climate change protection. Species distribution modeling was employed to identify freshwater ecosystems that are sensitive to climate change. Their results showed that five species would lose parts of their current suitable range due to climate change, while ten species would gain new suitable habitats. Native species are of special importance for conservation due to their limited ranges (Yousefi *et al*. 2020). According to the results of this study, species such as *L. brachycephalus* are on the threshold of vulnerability and decline. These species play an important role in the local economy and fishing industry, and reducing their loss can have serious economic and social consequences. Despite the importance of these resources and unique biodiversity, comprehensive studies and sufficient modeling on the effects of climate change on water ecosystems, especially in the southern basin of the Caspian Sea, have not been conducted by policymakers and managers. Therefore, regarding the effects of climate change on the distribution and survival of sensitive fish species, it is necessary to take action in this area to prevent the destruction of sensitive habitats and preserve the migration of species, remove barriers, create migration corridors, restore lost habitats, and implement other such measures (Ficke *et al*. 2007; Tamario *et al*. 2019; Thorstad *et al*. 2021; Rahel 2022). Vulnerable species can resist extreme changes (Schmutz et al. 2018; Mostafavi et al. 2022). Regarding these measures, to develop preventive strategies to reduce the effects of climate change on biodiversity, a relatively clear image is necessary to understand the future of this biodiversity under different scenarios of global climate change (Guisan *et al*. 2000; Bellard *et al*. 2012; Visconti *et al*. 2016; Corlett 2020; Ortiz *et al*. 2021; Barbarossa *et al*. 2021; Harrison *et al*. 2024). As stated in previous studies, the effects of climate change on aquatic life have clearly shown that species respond differently to climate change, and these responses provide appropriate management strategies and solutions. It is important to preserve any species (Mawdsley *et al*. 2009; Mustafavi *et al*. 2014, 2015, 2019, 2021, 2023; Bagheri *et al*. 2023; Datta *et al*. 2024; McClanahan *et al*. 2024; Farzi *et al*. 2024).

This study investigated the impact of climate change on the distribution of fish species in the Caspian Sea. These results, based on presence data, can be useful for planning future management scenarios, considering that climate models predict stronger impacts on freshwater fish. Therefore, possible conservation strategies that can be proposed to protect fish biodiversity under climate-induced impacts are: (i) maintaining ecological flow, as the natural variation of flow rate is necessary to sustain suitable habitats for freshwater fish; (ii) restoring the connection of rivers to create opportunities for fish species with low temperature tolerance to move towards optimal temperatures, taking into account the possibility of maintaining barriers; (iii) determining and creating conservation areas where independent collections are preserved, thus playing a key role in maintaining biodiversity; (iv) improving water quality in polluted rivers to reduce human stressors; and (v) restoring coastal areas to create shade and direct cooling effects on river temperature. Currently, there is no doubt that the increase in human activities and pressures is responsible for climate change, which has direct and indirect effects on freshwater ecosystems. Considering that the studied species is in the UV category on the IUCN list and is one of the valuable species of the Caspian Sea Basin, these results provide useful information in the field of species and habitat management and protection. Managers can use the results of this research to provide various solutions for the protection of freshwater species and ecosystems.

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