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ORIGINAL ARTICLE

How does ensemble species distribution modeling under climate change reveal habitat loss for a Tigris–Euphrates endemic fish (*Luciobarbus xanthopterus* Heckel, 1843) in Iran?

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Abstract
Climate change is expected to alter the distribution and persistence of freshwater fishes, particularly endemic species with geographically restricted ranges. An ensemble species distribution modelling (SDM) framework implemented in biomod2 to estimate current habitat suitability for the vulnerable yellowfin barbel (*Luciobarbus xanthopterus*) and to project changes under future climate scenarios. After spatial filtering, 42 occurrence records were retained. Nineteen bioclimatic variables, elevation, and human footprint were initially considered; after reducing multicollinearity, six predictors were retained: annual mean temperature, annual precipitation, temperature seasonality, precipitation of the wettest quarter, elevation, and human footprint. Six algorithms (ANN, RF, GLM, GBM, FDA, and MARS) were fitted and evaluated using AUC, TSS, and Cohen's kappa. The ensemble model identified approximately 68,000km² of currently suitable habitat, corresponding to about 40% of the Iranian portion of the Tigris basin. Under SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 (low, intermediate, high, and very high greenhouse gas emissions, respectively), projected habitat loss by 2070 was 24%, 25%, 33%, and 49%, respectively, whereas habitat gains were 15%, 14%, 8%, and 5%. Net habitat change ranged from -9% under SSP1-2.6 to -44% under SSP5-8.5. Annual mean temperature, annual precipitation, temperature seasonality, and human footprint were the most influential predictors. These results indicate that climate change may substantially reduce the suitable range of *L. xanthopterus* and highlight the value of identifying climate refugia, maintaining river connectivity, and reducing non-climatic pressures in the Tigris–Euphrates system.

Keywords: Biodiversity, Freshwater ecosystem, Gattan, Habitat loss, Karun, Tigris Basin

INTRODUCTION

Climate change is reshaping freshwater ecosystems through increasing temperatures, altered precipitation regimes, and more frequent climatic extremes. Freshwater fishes are particularly sensitive because their distributions are constrained by thermal conditions, hydrological regimes, habitat connectivity, and the fragmented structure of river networks. These constraints can be especially important for endemic and range-restricted fishes in semi-arid regions, where changes in temperature and water availability can interact with existing habitat degradation and other anthropogenic pressures (Reid et al. 2019; Whitfield et al. 2023).

Iran's freshwater ichthyofauna is characterized by substantial endemism and occurs across environmentally heterogeneous drainage basins. The Tigris–Euphrates system supports numerous native fishes and faces multiple pressures, including habitat modification, water abstraction, pollution, and other human disturbances (Moghadam & Kambouzia 2021; Jouladeh-Roudbar et al. 2020). Climate-related changes therefore need to be considered together with non-climatic pressures when assessing the future distribution of freshwater species.

The yellowfin barbel, *Luciobarbus xanthopterus* Heckel, 1843, is a large cyprinid associated with the Tigris–Euphrates basin and is listed as Vulnerable (Freyhof 2014). In Iran, it is found in the Tigris drainage, including the Karun and Karkheh rivers and associated wetlands (Eagderi et al. 2022; Çiçek et al. 2023; Sayyadzadeh & Esmaeili 2024). The species primarily inhabits large lowland rivers, lakes, and wetlands and appears to be more dependent on

riverine and wetland habitats than some other large *Luciobarbus* species (Freyhof 2014). Although it also occurs in reservoirs, it migrates into inflowing rivers to spawn, using shallow areas with gravel substrates at depths of approximately 30–150 cm (Freyhof 2014). As a large riverine and wetland-associated freshwater fish, its persistence may be affected by the combined effects of climatic change, altered hydrological regimes, habitat modification, and loss of suitable spawning and wetland habitats (Hussain et al. 2008; Mostafavi et al. 2021). Accordingly, climate change may exacerbate existing threats, further affecting habitat availability and suitability.

Previous modelling studies provide evidence that climate change can alter the distribution of Iranian freshwater fishes. Darab et al. (2020) modelled habitat suitability of *Cyprinion tenuiradius* in Fars Province using MaxEnt and identified climatic and environmental variables as important determinants of habitat suitability under future climate scenarios. Makki et al. (2021) modelled climate-change effects on the spatial distribution of *Garra rufa*, while Makki et al. (2023) assessed climate-heating impacts on riverine fish species diversity across a biodiversity hotspot in Iran. Rezaei et al. (2024) evaluated climate-change impacts on the distribution of *Luciobarbus esocinus* under multiple climate scenarios. More broadly, Masoumi et al. (2024) documented climate-related shifts in the spatial ranges of endemic fishes in the semi-arid Arabian Peninsula. A recent study on *Luciobarbus* species in the Tigris–Euphrates basin has also emphasized the importance of macroecological predictors and future refugia for conservation planning (Khoshnamvand et al. 2025). Together, these studies demonstrate the relevance of species distribution modelling (SDM) for evaluating climate-related distributional changes, but they do not provide a species-specific ensemble assessment of future habitat change for *L. xanthopterus*.

Species distribution models provide a quantitative framework for relating occurrence records to environmental predictors and projecting habitat suitability under alternative environmental conditions. Ensemble approaches can combine predictions from several algorithms and thereby reduce dependence on the assumptions of a single modelling technique (Thuiller et al. 2009; Harris et al. 2024). For freshwater fishes, such approaches can help identify areas of current suitability, potential future habitat, and locations that may function as climate refugia.

Environmental predictors included in freshwater fish distribution models represent complementary aspects of climatic suitability, hydrological conditions, landscape structure, and anthropogenic disturbance. Temperature influences fish metabolic rates, physiological performance, and thermal tolerance (Buisson et al. 2008; Bonacina et al. 2023), whereas precipitation affects water availability and can influence river discharge, wetland extent, and aquatic habitat persistence. Temperature and precipitation seasonality may be particularly important in semi-arid regions, where seasonal climatic fluctuations can alter hydrological conditions and the availability of suitable habitats. Elevation represents broad-scale environmental gradients and may indirectly reflect variation in temperature, topography, and river characteristics. In addition, the human footprint indicates anthropogenic pressures that may affect freshwater habitats through infrastructure development, water abstraction, pollution, and habitat modification (Sanderson et al. 2002; McComb & Cushman 2020). These factors are relevant to *L. xanthopterus*, which inhabits large lowland rivers, lakes, and marshes and uses shallow river habitats for spawning (Freyhof 2014). Considering these complementary predictors can therefore help identify the environmental conditions associated with the species' distribution and assess how climate change and human pressures may influence its future habitat suitability.

Accordingly, this study addresses a specific knowledge gap by applying an ensemble SDM to *L. xanthopterus* within the Iranian portion of the Tigris Basin. The study had three objectives: (1) to map current suitable habitat using six statistical and machine-learning algorithms; (2) to quantify habitat loss, gain, and net change under four Shared Socio-economic Pathways (SSPs) scenarios for the 2061–

2080 period, representing the climate around 2070; and (3) to identify the environmental predictors that contribute most strongly to the predicted distribution. The results are intended to provide a spatial basis for interpreting climate vulnerability and informing freshwater conservation planning.

MATERIALS AND METHODS

The analysis followed an ensemble SDM framework in which occurrence records were related to climatic, topographic, and anthropogenic predictors, individual algorithms were evaluated using independent testing subsets, and a performance-weighted ensemble was used to estimate current and future habitat suitability. The general approach follows established ensemble-modelling practice implemented in biomod2 (Thuiller et al. 2009) and recent applications of SDMs to freshwater fishes under climate change (Darab et al. 2020; Makki et al. 2021; Harris et al. 2024).

Study area: The study covered Iran (approximately 1.648 million km²), with particular attention to the Iranian portion of the Tigris basin, which represents the core area of *L. xanthopterus* occurrence in Iran (Figs. 1 and 2). In the Tigris basin, this species occurs in the Karun, Karkheh, and Jarahi rivers and the Hur al-Azim Marsh, which provide habitat (Keivany et al. 2016). The spatial focus was selected to encompass the known distribution of the focal species while allowing the model to evaluate potentially suitable areas beyond currently occupied locations.

Occurrence data and spatial filtering: Occurrence records of *L. xanthopterus* were compiled from field surveys, the Global Biodiversity Information Facility (GBIF), and published literature. Spatial thinning and bias correction are essential steps in species distribution modeling (Aiello-Lammens et al. 2015; Beck et al. 2014; Steen et al. 2021). To reduce spatial clustering and the potential influence of uneven sampling effort on model calibration, occurrence records were spatially filtered using the biomod2 package in R, applying a minimum distance of 1km between retained records. This procedure reduced the influence of closely clustered observations while

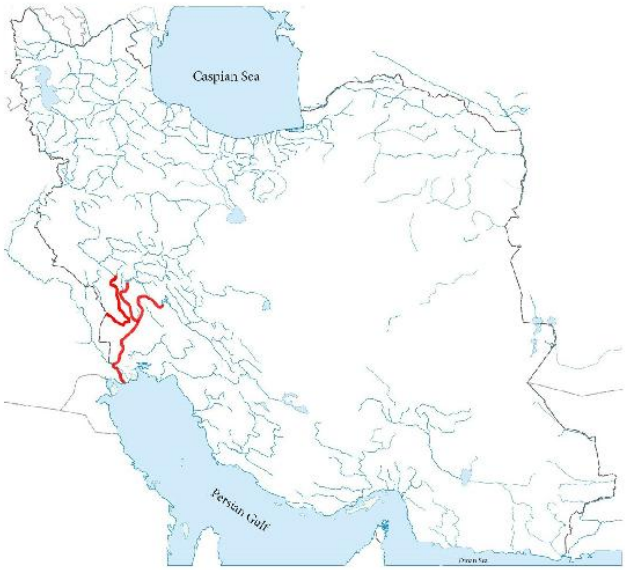


Fig.1. Geographic distribution of the *Luciobarbus xanthopterus* in Iran (source data: Jouladeh-Roudbar et al. 2020).

retaining spatially independent occurrence records for model development. Following spatial filtering, 42 spatially thinned presence records were retained for species distribution modelling.

Environmental predictors and multicollinearity screening: Bioclimatic variables, elevation, and the human footprint index were initially considered based on their ecological relevance to freshwater fish distribution and the habitat requirements of *L. xanthopterus*. Nineteen bioclimatic variables (Bio1–Bio19) were obtained from the WorldClim-Global Climate Database (https://www.worldclim. org/), representing baseline climate conditions for 1970-2000 (Table S1), at a spatial resolution of 30 arc-seconds (approximately 1km at the equator; Fick & Hijmans, 2017). Elevation was obtained from the WorldClim 2.1 elevation layer at the same nominal resolution. Future bioclimatic predictors were obtained from the WorldClim CMIP6 downscaled climate projections for the MRI-ESM2-0 general circulation model, under SSP1-2.6 and SSP5-8.5 for 2061–2080 (representative of 2070). WorldClim's CMIP6 projections are downscaled and bias-corrected using WorldClim 2.1 as the baseline climate dataset. The environmental layers were harmonized to a common spatial resolution and extent. Pairwise Pearson correlations were examined, and highly

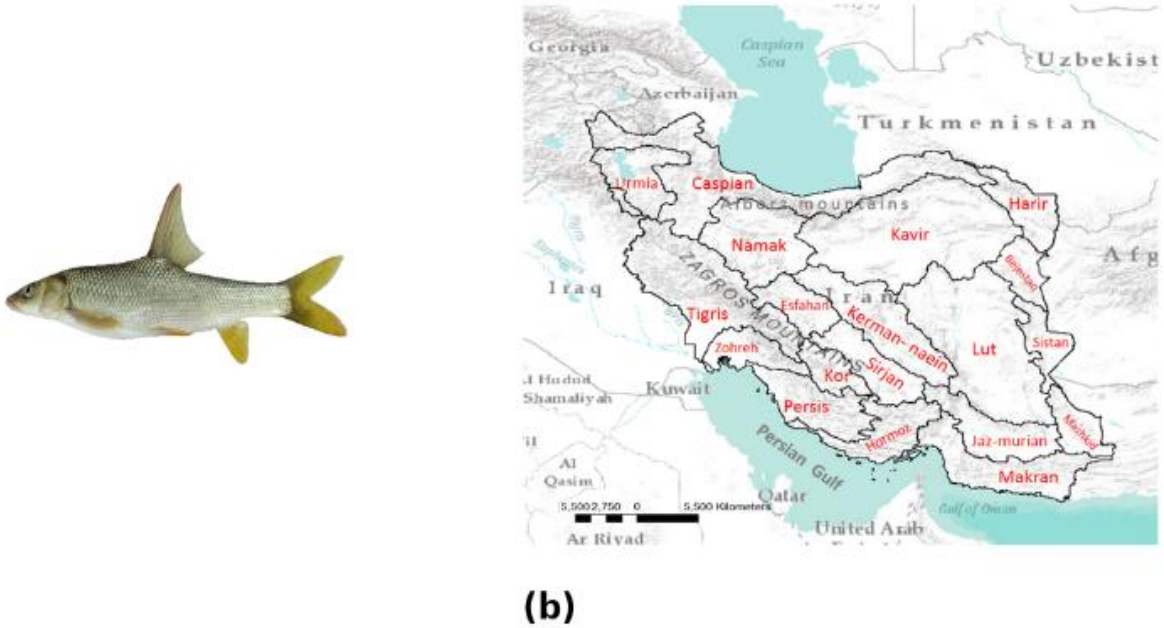


Fig.2. (**a**) Yellowfin barbel reference image and (**b**) geographic/drainage context.

correlated variables with |r| ≥ 0.70 were removed to reduce multicollinearity. Six predictors were retained for the final models: Bio1 (annual mean temperature), Bio4 (temperature seasonality), Bio12 (annual precipitation), Bio16 (precipitation of the wettest quarter), elevation, and human footprint. Including human footprint was intended to represent an important non-climatic component of habitat suitability, consistent with the recognition that climatic and anthropogenic pressures can act together on freshwater biodiversity (Sanderson et al. 2002; McComb & Cushman 2020).

Ensemble modelling: To map the current distribution of the species, a multi-model ensemble approach based on Thuiller et al. (2009) was implemented using the biomod2 package (Thuiller et al., 2019) in R v.4.5.2. Six algorithms were fitted: Artificial Neural Networks (ANN), Random Forest (RF), Generalized Linear Models (GLM), Generalized Boosted Models (GBM), Flexible Discriminant Analysis (FDA), and Multivariate Adaptive Regression Splines (MARS). Pseudo-absence records were generated in equal number to the presence records and were constrained by a 1-km buffer around presence locations. For each modelling run, 80% of the available records were used for calibration and 20% for evaluation, and this partitioning was repeated 10 times. Model performance was evaluated using the Area Under the Receiver Operating Characteristic Curve (AUC), True Skill Statistic (TSS), and Cohen's kappa. The final ensemble prediction was generated by combining the individual algorithm predictions according to their model performance within the biomod2 framework. Using multiple complementary algorithms and an ensemble prediction follows the multi-model approach described by Thuiller et al. (2009) and subsequent ensemble SDM applications (Harris et al. 2024). Given the relatively small number of spatially thinned occurrence records (n = 42), model predictions were interpreted cautiously, particularly regarding potential overfitting and uncertainty in fine-scale habitat suitability.

Future climate scenarios and habitat-change analysis: Future bioclimatic layers for the 2061–2080 period, hereafter referred to as the 2070 projection, were obtained from the WorldClim database using the MRI-ESM2-0 general circulation model developed by the Meteorological Research Institute of Japan. Four Shared Socioeconomic Pathways (SSPs): SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. These scenarios

Table 1. Performance metrics of the six individual algorithms used in the ensemble model.

Algorithm	AUC	TSS	Cohen's kappa
GLM	0.88	0.60	0.53
RF	0.99	0.99	0.99
ANN	0.87	0.64	0.52
GBM	0.96	0.84	0.68
MARS	0.91	0.69	0.56
FDA	0.89	0.61	0.53

represent low, intermediate, high, and very high greenhouse gas emissions and different levels of radiative forcing. We used them to test how sensitive projected habitat suitability is to different future climates. These scenarios were chosen because they span a wide range of possible future climates. The future climate layers were provided at a spatial resolution of 30 arc-seconds (approximately 1km) and are based on the WorldClim downscaling and bias-correction framework**.**

Current habitat suitability was modelled using the WorldClim baseline bioclimatic variables for the 1970–2000 period. Continuous ensemble suitability predictions were converted into binary suitable/unsuitable surfaces using a threshold derived from the receiver operating characteristic (ROC) curve. For each future scenario, habitat loss was calculated as the area classified as suitable under current conditions but unsuitable under future conditions, and habitat gain as the area classified as unsuitable under current conditions but suitable under future conditions. Net habitat change was calculated as habitat gain minus habitat loss.

RESULTS

Model performance: The six algorithms differed in predictive performance across the three evaluation metrics (Table 1). AUC values ranged from 0.87 to 0.99, TSS values from 0.60 to 0.99, and Cohen's kappa values from 0.52 to 0.99. Random Forest (RF) showed the highest performance across all three metrics (AUC= 0.99, TSS= 0.99, and kappa= 0.99), followed by Gradient Boosting Machine (GBM; AUC= 0.96, TSS= 0.84, and kappa= 0.68). Multivariate Adaptive Regression Splines (MARS) showed intermediate performance (AUC= 0.91, TSS= 0.69, and kappa= 0.56), whereas the Generalized Linear Model (GLM), Flexible Discriminant Analysis (FDA), and Artificial Neural Network (ANN) showed lower agreement according to TSS and Cohen's kappa. Among these algorithms, ANN had the lowest AUC (0.87) and kappa (0.52), while GLM had the lowest TSS (0.60). Overall, although AUC values indicated good to excellent discrimination across the algorithms, the TSS and kappa values indicated variable classification performance, ranging from moderate to very high. These results demonstrate differences among individual algorithms and provide context for evaluating the final ensemble prediction.

Current habitat suitability: The ensemble prediction estimated approximately 68,000 km² of currently suitable habitat, corresponding to roughly 40% of the Iranian portion of the Tigris basin. Predicted suitable areas were concentrated mainly along the middle and lower reaches of the Karun and Karkheh rivers and their associated wetlands (Fig. 4). This spatial pattern indicates that the predicted distribution of *L. xanthopterus* is concentrated within parts of the Tigris drainage system.

Relative importance of environmental predictors: The variable-importance analysis identified annual mean temperature, annual precipitation, temperature seasonality, and human footprint as the four most influential predictors (Fig. 3). Their average relative contributions were approximately 24.6%, 24.3%, 16.9%, and 14.6%, respectively. The remaining predictors—precipitation of the wettest quarter and elevation—contributed less to the ensemble prediction. Figure 3 presents response curves for the most influential predictors, allowing examination of the relationship between environmental gradients and predicted suitability.

The response curves revealed distinct relationships between predicted habitat suitability and the four most

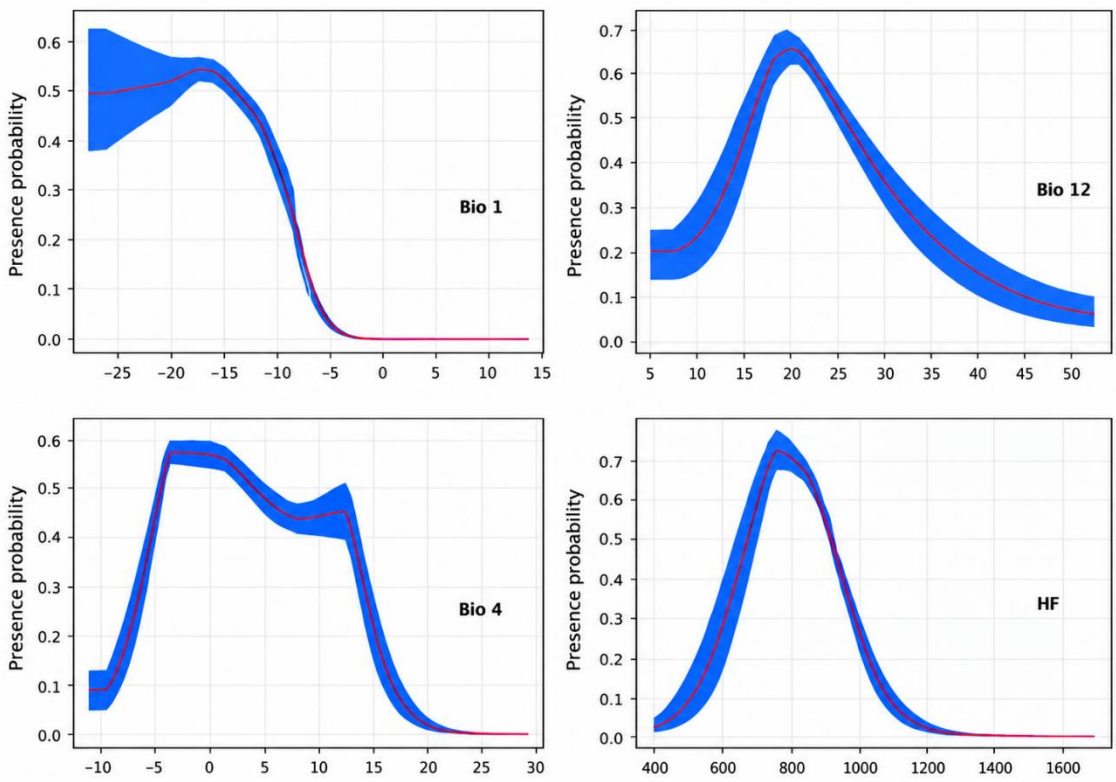


Fig.3. Relative importance of environmental predictors and response curves for the ensemble habitat-suitability model of *Luciobarbus xanthopterus*, including annual mean temperature (Bio1), temperature seasonality (Bio4), annual precipitation (Bio12), and human footprint (HF). The response curves represent this performance-weighted ensemble prediction and were generated using the default parameter settings within the biomod2 framework. To generate the curves, the focal predictor was varied across its range while all other environmental variables were held constant at their respective mean values. The red solid line represents the mean predicted habitat suitability across 10 cross-validation runs, and the blue shaded area indicates the model uncertainty among the runs.

Table 2. Projected changes in suitable habitat for *Luciobarbus xanthopterus* by 2070 under SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 using the MRI-ESM2-0 climate model.

Scenario	Total Habitat Area (km²)	Habitat lost (km²)	New habitat gained (km²)	Net change
Current	68,000	0	0	0
SSP1-2.6	61,092	17,123 (24%)	10,215 (15%)	−9%
SSP2-4.5	61,400	17,343 (25%)	10,743 (14%)	−11%
SSP3-7.0	48,960	24,480 (33%)	5,440 (8%)	−25%
SSP5-8.5	38,080	33,320 (49%)	3,400 (5%)	−44%

influential environmental predictors (Fig. 3). For annual mean temperature (Bio1), predicted suitability remained relatively stable at the lower end of the temperature gradient until approximately −12°C, after which it declined sharply until around −2°C and then remained relatively stable. Annual precipitation (Bio12) showed a unimodal, bell-shaped relationship, with predicted suitability peaking at approximately 20-25 units and declining toward both lower and higher precipitation values across a response range of approximately 5-50. Temperature seasonality (Bio4) exhibited a more complex, bimodal pattern, with a primary peak around -2, followed by a decline and a smaller secondary peak around 12. Suitability subsequently declined towards approximately 18, beyond which the response became relatively stable. Human footprint showed a unimodal relationship, with the highest predicted suitability around a value of 800 within an approximate response range of 400-1,200, followed by a relatively stable response at higher values. Overall, these curves indicate that predicted habitat suitability varies nonlinearly across

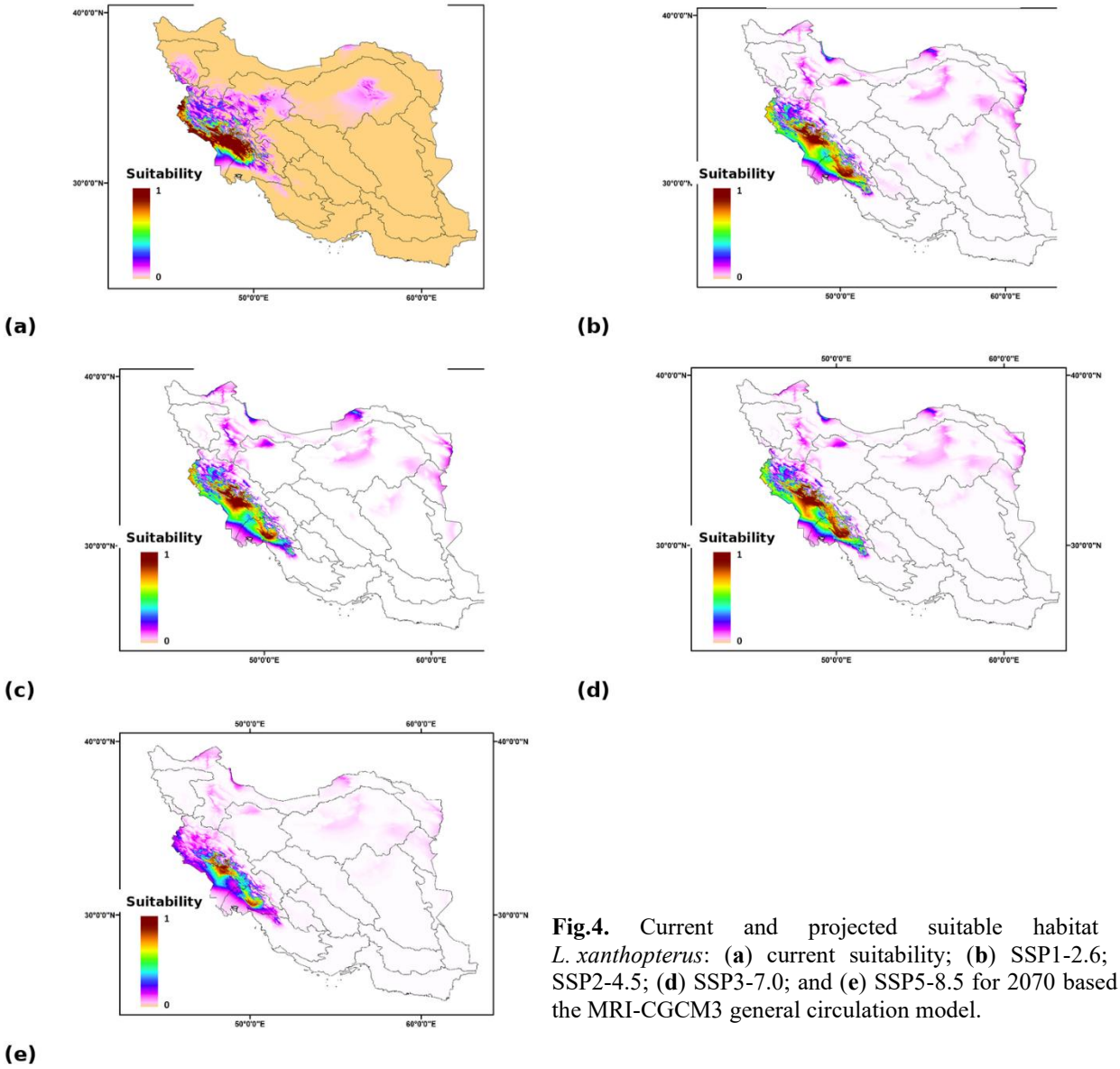


Fig.4. Current and projected suitable habitat of *L. xanthopterus*: (**a**) current suitability; (**b**) SSP1-2.6; (**c**) SSP2-4.5; (**d**) SSP3-7.0; and (**e**) SSP5-8.5 for 2070 based on the MRI-CGCM3 general circulation model.

several climatic gradients and the human-footprint gradient, rather than changing uniformly with each predictor.

Projected habitat changes by 2070: The spatial projections indicated net habitat loss under all four climate scenarios (Fig. 4; Table 2). Under SSP1-2.6, approximately 17,123km² (24%) of current suitable habitat was lost, and 10,215km² (15%) of new habitat was gained, producing a net change of –9%. Under SSP2-4.5, habitat loss was approximately 17,343 km² (25%), habitat gain was 10,743km² (14%), and net change was –11%. Under SSP3-7.0, approximately 24,480km² (33%) of current habitat was lost, 5,4 40km² (8%) was gained, and net change was -25%. Under SSP5-8.5, approximately 33,320km² (49%) was lost, only 3,400km² (5%) was gained, and net change reached -44% (Table 2).

The spatial projections indicated a net reduction in suitable habitat under future climate scenarios (Fig. 4; Table 2). Habitat losses and gains were not distributed uniformly across the study area. The spatial projections suggested that losses were concentrated mainly in the southern and lower-elevation portions of the currently suitable range, whereas gains were more limited and appeared primarily in relatively northerly or higher-elevation areas of the basin (Fig. 4). This general spatial pattern was more pronounced under SSP5-8.5 than under SSP1-2.6.

DISCUSSION

Model performance, current habitat suitability, and environmental predictors: The six individual algorithms differed in predictive performance, with AUC values ranging from 0.87 to 0.99, TSS values from 0.60 to 0.99, and Cohen's kappa values from 0.52 to 0.99 (Table 1). Random Forest showed the highest scores across all three metrics, whereas other algorithms showed more moderate agreement on TSS and kappa. These differences highlight the importance of evaluating individual algorithms rather than assuming that all models perform equally well. The ensemble approach provides a framework for integrating predictions from multiple algorithms, although its performance should be assessed separately from that of the individual models. The relatively small number of spatially thinned presence records (n= 42) should also be considered when interpreting the predictions, because limited occurrence data can increase uncertainty in estimated habitat suitability. The ensemble's high performance supports using the selected environmental predictors to estimate the current distribution of *L. xanthopterus*. Ensemble approaches are particularly useful when predictions may vary among algorithms because they combine complementary modelling assumptions and can provide a more stable representation of habitat suitability (Thuiller et al. 2009; Harris et al. 2024).

The current ensemble projection identified approximately 68,000km² of suitable habitat within the Iranian portion of the Tigris basin, representing approximately 40% of the study area. Predicted suitability was concentrated mainly in the Karun and Karkheh river systems and their associated wetlands (Fig. 4). This pattern is broadly consistent with the species' known occurrence within the Tigris–Euphrates drainage. However, the predicted distribution reflects environmental suitability at the analysis's spatial resolution, not confirmation of occupancy at every predicted location. River connectivity, local habitat quality, and other ecological requirements may further influence whether apparently suitable locations can support populations (Jouladeh-Roudbar et al. 2020; Moghadam & Kambouzia 2021).

The importance of climatic predictors indicates that temperature and precipitation are key environmental correlates of the modelled distribution of *L. xanthopterus*. Annual mean temperature (Bio1; 24.6%) and annual precipitation (Bio12; 24.3%) were the two most influential predictors, followed by temperature seasonality (Bio4; 16.9%). Their response curves indicated nonlinear relationships between these variables and predicted suitability (Fig. 3). In particular, the unimodal response to annual precipitation suggests that the highest predicted suitability occurred within an intermediate portion of the modelled precipitation gradient, rather than increasing continuously with precipitation. The more complex response to temperature seasonality likewise indicates that suitability did not vary uniformly along this predictor. These relationships should be interpreted as modelled associations and not as direct evidence of physiological thresholds.

The importance of temperature and precipitation is consistent with previous studies of Iranian freshwater fishes. Darab et al. (2020), in a MaxEnt assessment of *Cyprinion tenuiradius* in Fars Province, identified climatic variables among the main determinants of habitat suitability and projected distributional changes under future scenarios. Makki et al. (2021) likewise demonstrated that climate change can alter the spatial distribution of *Garra rufa*. At a broader scale, Makki et al. (2023) showed that climate warming can affect riverine fish diversity in Iran. The present results therefore extend an established regional pattern to *L. xanthopterus* while providing an ensemble-based estimate of habitat change.

Human footprint was the fourth most influential predictor, with a mean relative contribution of 14.6%. This result indicates that the spatial pattern of predicted suitability was associated not only with climatic conditions but also with the human-footprint gradient. This interpretation is consistent with the broader freshwater-biodiversity literature emphasizing interacting and cumulative stressors (Reid et al. 2019; McComb & Cushman 2020). Including human footprint in the model therefore

explicitly represents an important non-climatic constraint on suitability. However, variable importance alone does not establish whether higher human-footprint values were associated with lower suitability throughout the study area. The response curve must be used to interpret the direction and shape of that relationship, and the human-footprint index should be treated as a broad proxy for anthropogenic influence rather than a direct measure of any individual pressure. In the Tigris–Euphrates system, potentially relevant pressures include water abstraction, dams and other barriers, pollution, and habitat modification. These pressures may interact with climatic changes by altering flow regimes, water availability, habitat quality, and opportunities for movement between river reaches. Nevertheless, the present model did not test these specific mechanisms directly, and the static human-footprint layer cannot distinguish among them.

Future habitat projections, changes, and conservation implications: The future projections indicate that the area and spatial distribution of suitable habitat may change under all assessed climate scenarios. The future projections indicate that the area and spatial distribution of suitable habitat may change under all assessed climate scenarios. The projections indicate progressively greater habitat loss from SSP1-2.6 to SSP5-8.5, with net changes of -9%, -11%, -25%, and -44%, respectively (Table 2; Fig. 4). The direction of this response is consistent with recent modelling of other Iranian cyprinids. Rezaei et al. (2024) reported climate-related distributional changes for *Luciobarbus esocinus* under alternative climate scenarios, while Khoshnamvand et al. (2025) emphasized future refugia and macroecological predictors for *Luciobarbus* species in the Tigris–Euphrates basin. Masoumi et al. (2024) similarly documented substantial spatial responses of endemic freshwater fishes to climate change in a semi-arid region. Although the species, spatial extent, predictor sets, and climate-model assumptions differ among these studies, their results collectively support the interpretation that endemic freshwater fishes in semi-arid Middle Eastern systems may experience substantial redistribution under future climate change.

The balance between lost and newly suitable habitat is important for conservation planning. If the corrected projections show that habitat loss exceeds habitat gain, newly suitable areas may not offset the loss of currently suitable habitat. Furthermore, newly suitable conditions do not necessarily indicate that the species will colonize those areas. The ability to reach them may depend on dispersal capacity, river-network configuration, flow conditions, and physical barriers. Because dispersal and connectivity were not explicitly modelled, the projections identify potential changes in environmental suitability rather than predicting actual range expansion or population movement.

The spatial outputs may help identify river reaches and sub-basins that retain suitable conditions under climate scenarios. Such areas could be considered candidates for further field assessment and conservation attention. Specific priority reaches should, however, be identified from the overlapping suitable-habitat maps for SSPs scenarios, rather than inferred from the general pattern of current suitability alone. Maintaining riverine habitat quality and reducing avoidable anthropogenic pressures may be important management considerations, particularly where suitable habitat overlaps with heavily modified river systems. These recommendations follow from the potential consequences of habitat change and general freshwater-ecology principles; they should not be interpreted as outcomes of a connectivity analysis, which this study did not include.

Several limitations should be considered when interpreting these projections. First, future predictions were based on a single general circulation model (MRI-CGCM3); using multiple GCMs and calculating a consensus projection would allow climate-model uncertainty to be evaluated more explicitly. Second, the model did not include several local-scale habitat variables that may be important for freshwater fishes, such as dissolved oxygen, salinity, detailed riverbed structure, flow characteristics, and migration barriers. Third, SDMs generally assume the relationship between the species and environmental predictors remains sufficiently stable for future

projections, whereas ecological adaptation or acclimation could alter that relationship. These limitations define priorities for future work and should be considered when translating model outputs into local management decisions. In riverine systems, opportunities for redistribution can also depend on longitudinal connectivity and the absence of physical barriers. For this reason, identifying areas that remain suitable across scenarios and maintaining connectivity among suitable river segments may be useful components of conservation planning, consistent with recent work on refugia and freshwater connectivity (Pavey et al. 2017; Khoshnamvand et al. 2025; Van Rees et al. 2021).

Despite these limitations, the study provides a spatial assessment of current habitat suitability and potential future changes for *L. xanthopterus* in the Iranian Tigris basin. Combining future SDM projections with field surveys, hydrological information, and assessments of river connectivity would help evaluate the persistence of suitable habitat and support more locally targeted conservation planning.

From a management perspective, the spatial outputs can identify areas that remain suitable across multiple scenarios, support connectivity among suitable river segments, and prioritize reducing non-climatic pressures such as habitat degradation, pollution, overfishing, and fragmentation. These measures should be interpreted as management implications from the spatial projections rather than evidence that climate change is the sole driver of future distribution. Integrating climatic projections with local ecological data and freshwater-management planning would provide a stronger basis for conservation of *L. xanthopterus* and other endemic fishes in the Tigris–Euphrates system (Van Rees et al. 2021; Khoshnamvand et al. 2025). Furthermore, the limited area of newly suitable habitat is also important for conservation interpretation. Under SSP5-8.5, only 5% of the current suitable area is projected to become newly suitable, compared with 49% loss. This imbalance suggests that potential range expansion may not compensate for losses within the present distribution.

Limitations associated with occurrence data: An important limitation of this study is the relatively small number of occurrence records available after spatial filtering. Although 42 spatially thinned records provided a basis for modelling, the adequacy of this sample depends on the species' prevalence, the environmental and geographic representativeness of the records, and the complexity of the fitted models (van Proosdij et al. 2016). Limited occurrence data may increase uncertainty in predicted habitat suitability and the estimated importance of individual predictors, particularly when several algorithms are used. Spatial thinning also involves a trade-off between reducing the influence of clustered sampling and retaining potentially useful occurrence information. Therefore, the predicted distribution and relative importance of environmental predictors should be interpreted with appropriate caution. Future studies that incorporate additional, systematically collected records and evaluate sensitivity to spatial-filtering distances could improve the robustness of distribution estimates for *L. xanthopterus*.

CONCLUSIONS

This study used an ensemble of six species-distribution modelling algorithms to estimate current and future habitat suitability for the Vulnerable yellowfin barbel, *L. xanthopterus*, in the Iranian portion of the Tigris basin. Approximately 68,000 km² was predicted to be currently suitable. Annual mean temperature, annual precipitation, temperature seasonality, and human footprint were the four most influential predictors, together accounting for 80.4% of the reported mean relative importance. All four 2070 scenarios indicated net habitat loss, ranging from –9% under SSP1-2.6 to –44% under SSP5-8.5, with increasingly limited habitat gains under higher-emission scenarios.

The magnitude of projected habitat loss and gain should be interpreted in light of uncertainty associated with using a single climate model, the limited occurrence dataset, and the omission of detailed hydrological and local habitat variables. The resulting

maps may help identify areas that remain suitable across scenarios and guide subsequent field assessments. Future studies integrating multiple climate models, hydrological data, and river-connectivity assessments would provide a stronger basis for evaluating habitat persistence and supporting conservation planning for this species.

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Appendix

Table S1. Listing all 19 initial bioclimatic variables. Source: WorldClim version 2.1; Fick & Hijmans (2017)

Code	Bioclimatic variable
Bio1	Annual mean temperature
Bio2	Mean diurnal temperature range
Bio3	Isothermality
Bio4	Temperature seasonality
Bio5	Maximum temperature of the warmest month
Bio6	Minimum temperature of the coldest month
Bio7	Temperature annual range
Bio8	Mean temperature of the wettest quarter
Bio9	Mean temperature of the driest quarter
Bio10	Mean temperature of the warmest quarter
Bio11	Mean temperature of the coldest quarter
Bio12	Annual precipitation
Bio13	Precipitation of the wettest month
Bio14	Precipitation of the driest month
Bio15	Precipitation seasonality
Bio16	Precipitation of the wettest quarter
Bio17	Precipitation of the driest quarter
Bio18	Precipitation of the warmest quarter
Bio19	Precipitation of the coldest quarter

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مقاله کامل

چطور مدل‌سازی تجمعی پراکنش گونه‌ای، از بین رفتن زیستگاه یک ماهی بومزاد حوضه دجله–فرات؛ (*Luciobarbus xanthopterus* Heckel, 1843) تحت تأثیر تغییر اقلیم در ایران را نمایش می‌دهد؟

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چکیده: انتظار می‌رود تغییرات اقلیمی، پراکنش و حیات جمعیت ماهیان آب شیرین را تحت تأثیر قرار دهد؛ این تأثیر به‌ویژه در مورد گونه‌های بومی با دامنه پراکنش جغرافیایی محدود، قابل ملاحظه‌تر خواهد بود. در این پژوهش، با استفاده از چارچوب مدل‌سازی تجمعی پراکنش گونه‌ای (Ensemble Species Distribution Modelling؛ SDM) که با بسته biomod2 در بستر R پیاده‌سازی شده است، مطلوبیت زیستگاه کنونی ماهی آسیب‌پذیر گطان (*Luciobarbus xanthopterus*) برآورد و تغییرات احتمالی آن تحت سناریوهای اقلیمی آینده پیش‌بینی شد. پس از اعمال اصلاحات مکانی، ۴۲ نقطه حضور گونه برای تحلیل حفظ شد. در ابتدا، ۱۹ متغیر زیست‌اقلیمی، ارتفاع از سطح دریا و شاخص اثرگذاری انسانی مورد بررسی قرار گرفتند؛ سپس، پس از کاهش هم‌خطی چندگانه، شش متغیر پیش‌بینی شامل میانگین دمای سالانه، بارش سالانه، تغییرات فصلی دما، بارش در مرطوب‌ترین فصل سه‌ماهه، ارتفاع و شاخص اثرگذاری انسانی انتخاب شدند. شش الگوریتم شامل شبکه عصبی مصنوعی (ANN)، جنگل تصادفی (RF)، رگرسیون خطی تعمیم‌یافته (GLM)، تقویت گرادیانی (GBM)، تحلیل تفکیک انعطاف‌پذیر (FDA) و رگرسیون چندگانه تطبیقی اسپلاین (MARS) برازش داده شدند و عملکرد آنها با استفاده از شاخص‌های سطح زیر منحنی (AUC)، مهارت واقعی (TSS) و کاپای کوهن (Cohen's kappa) ارزیابی شد. مدل تجمعی نشان داد که در شرایط کنونی، حدود ۶۸,۰۰۰ کیلومترمربع از زیستگاه برای این گونه مناسب است که تقریباً معادل ۴۰ درصد از بخش ایرانی حوضه دجله است. براساس سناریوهای SSP1-2.6، SSP2-4.5، SSP3-7.0 و SSP5-8.5 (به‌ترتیب نماینده انتشار کم، متوسط، زیاد و خیلی زیاد گازهای گلخانه‌ای)، میزان کاهش زیستگاه پیش‌بینی‌شده تا سال ۲۰۷۰ به‌ترتیب ۲۴، ۲۵، ۳۳ و ۴۹ درصد خواهد بود؛ در مقابل، افزایش زیستگاه به‌ترتیب ۱۵، ۱۴، ۸ و ۵ درصد برآورد شد. در نتیجه، تغییر خالص زیستگاه از ۹- درصد در سناریوی SSP1-2.6 تا ۴۴- درصد در سناریوی SSP5-8.5 متغیر بود. میانگین دمای سالانه، بارش سالانه، تغییرات فصلی دما و شاخص اثرگذاری انسانی مهم‌ترین متغیرهای پیش‌بینی در مدل بودند. این نتایج نشان می‌دهند که تغییر اقلیم می‌تواند دامنه پراکنش زیستگاه‌های مناسب *L. xanthopterus* را به میزان قابل‌توجهی کاهش دهد. ازاین‌رو، شناسایی پناهگاه‌های اقلیمی، حفظ پیوستگی رودخانه‌ای و کاهش فشارهای غیر اقلیمی در حوضه دجله–فرات از اهمیت ویژه‌ای برخوردار است.

کلمات‌کلیدی: تنوع زیستی، اکوسیستم آب شیرین، گطان، از دست رفتن زیستگاه، کارون، حوضه دجله