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PRIMARY RESEARCH PAPER

The effects of climate change on the potential distribution of a frugivorous fish in the Amazon basin

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Abstract We assessed the effects of climate change on the geographic distribution of *Piaractus brachypomus* Cuvier (1818), a species of economic interest in the Amazon basin, using ecological niche models. We employed a set of five algorithms under the ensemble forecasting approach to predict the geographic distribution of the species in the present and in the future considering different carbon emission scenarios. The projections indicate that a large portion of the Amazon basin presents suitable areas for *P. brachypomus*, with moderate reduction of these areas in the near future. By 2090, under the pessimistic scenario, losses intensify, and the most drastic contractions are projected for the Branco, Japurá, Mamoré, Negro, and Purus sub-basins, while by the end of the century, suitable areas are predicted to occur mainly in rivers of the southwestern and central Amazon regions. The gain of suitable areas was smaller compared to the proportion of stable areas and losses. These results provide valuable information for the development of effective conservation plans with the intent of

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ensuring the ecological and economic benefits that *P. brachypomus* provides in the Amazon basin.

Keywords Ecological niche modeling · Conservation strategies · Distribuição potencial · *Piaractus brachypomus*

Introduction

Freshwater biodiversity is highly vulnerable to climate change (Capon et al., 2021; Korkmaz et al., 2023), being fish among the most threatened taxa (Markovic et al., 2019; Barbarossa et al., 2021). The susceptibility of freshwater fish to climate alterations is largely attributed to their dependence on hydrological and temperature regimes (Segurado et al., 2016; Lopes et al., 2018; Barbarossa et al., 2021). Changes in the precipitation dynamics alter the hydrological cycle, which is particularly concerning for Neotropical migratory fish, as they rely on natural flow dynamics for successful reproduction (Agostinho et al., 2003; Bailly et al., 2008; Barradas et al., 2012; Lopes et al., 2018). Furthermore, temperature changes might also be critical since gonadal development and spawning of migratory fish are primarily synchronized by environmental temperature and photoperiod (Vazzoler, 1996; Suzuki et al., 2004; Lopes et al., 2018; Devkota and Kathayat, 2020). Thus, abrupt changes in temperature, in particular outside the ideal range of the species, can result in low-quality oocytes, inhibiting reproduction (Targońska et al., 2014) or stimulating follicular atresia (Dorts et al., 2012), compromising the reproductive success of fish species. Therefore, any changes in such climate parameters can severely impact the behavior and life cycle of Neotropical fish (Jones, 2011; Fenkes, et al., 2016; Liu et al., 2021). Recent studies in the Neotropical region have revealed that climate change is impacting both the geographic distribution of fish fauna and the sustainability of their populations (Lopes et al., 2018; Ruaro et al., 2019; Bailly et al., 2021; Peluso et al., 2022, 2023).

In addition to climate change, river fragmentation is an imminent threat that is likely to change fish distribution (Peluso et al., 2022). Access to suitable areas in the future may be compromised if physical or ecological barriers, such as dams and reservoirs, block the path of migratory species (Campos et al., 2019). In this context, dams and reservoirs could further exacerbate the impacts of climate change on these species (Peluso et al., 2023). Combined with climate change, these and other anthropogenic activities can reshape the range of climate-environmental attributes, decreasing the habitat suitability of many fish species at large areas, thus contributing to population declines and local extirpations (Filipe et al., 2012; Lopes et al., 2017; Pecl et al., 2017; Nagelkerken et al., 2023). Among the Neotropical migratory fish species, *Piaractus brachypomus* Cuvier (1818), commonly known as "pirapitinga", belongs to the Serrasalmidae, occurring endemically in the Amazon River basins (Escobar et al., 2019). The species is commercially important as a fishing resource in Colombia, Peru, Bolivia, Venezuela, and Brazil (Loubens & Panini, 2001; Goulding et al., 2018; Cajado et al., 2020). In addition to its economic relevance, *P. brachypomus* play an important ecological role as frugivore fish and an effective seed disperser of a plethora of forest plant species (Correa et al., 2015). Frugivorous species have a profound role in recruitment dynamics, distribution patterns, and maintenance of regional plant diversity in the Amazon forest (Correa et al., 2015). Recent studies on the role of frugivorous fish in the Amazon have shown that they play a significant part in increasing seed dispersal in forests, thereby acting as an important link between aquatic and terrestrial ecosystems (Correa et al., 2025). Therefore, conservation measures that prioritize frugivore species like *P. brachypomus* are necessary, as changes in their populations can trigger effects on community structure, disrupt ecological interactions, and compromise local economies that depend on this resource.

Considering that climate change is altering the distribution patterns of freshwater fishes at various spatiotemporal scales, there is a growing need to predict how and where these changes will take place, particularly for seed-dispersing species, and define appropriate conservation strategies to avoid impacts on interacting species, communities, and ecosystems (Nuon et al., 2024). Ecological niche modeling (Peterson & Soberón, 2012) is a valuable tool for predicting geographic distribution patterns of species and their suitable habitats based on bioclimatic variables (Peterson

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et al., 2011; Peterson and Soberón, 2012; Chauhan et al., 2022). This approach is commonly used in the context of climate change, where understanding future distribution patterns is essential for identifying refuge areas and addressing conservation and social planning issues (Lopes et al., 2017; Ruaro et al., 2019).

This study aimed to assess the effects of climate change on the geographic distribution of the frugivorous fish *P. brachypomus* in the Amazon basin. First, we investigated the potential distribution of the species under current and future (2050 and 2090) climate scenarios considering both moderate (SSP2-4.5) and pessimistic (and SSP5-8.5) carbon emission pathways. Subsequently, we conducted spatial predictions to identify areas suitable for the occurrence of the species under future climate scenarios.. We expect that our findings will contribute to the development of conservation strategies for *P. brachypomus* in the Amazon basin, with particular emphasis on identifying climatically suitable areas for the species.. This approach prioritizes the preservation of ecosystem structure and processes in the long term while ensuring that the related socioeconomic activities can be sustained.

Material and methods

Study area

The Amazon River basin, covering approximately 7 million km^2, is the largest on the planet, representing approximately 6% of the Earth's surface (OTCA, 2023). It is a transboundary basin that extends across Brazil (63.9%), Peru (15.6%), Bolivia (11.7%), Colombia (5.6%), Ecuador (2.1%), Venezuela (0.9%) and French Guiana (0.2%) (Agência Nacional de Águas, 2012; FAO, 2015). The Amazon River's intricate hydrographic system, comprising over a thousand tributaries that collectively contribute to its 6,900 km expanse, is responsible for approximately 20% of the discharge of fresh water into the world's oceans (OTCA, 2023). It is bounded by the Andes Mountains to the west, the Guiana Plateau to the north, the Central Plateau to the south, and the Atlantic Ocean to the east (IBGE, 2010).

The basin features a complex network of interconnected aquatic and terrestrial ecosystems, including vast floodplains, large oxbow lakes, forests, and a complex hydrological hierarchy (Venticinque et al., 2021). The extensive longitudinal and lateral river connectivity of the basin is vital for the movement of water, sediments, nutrients, and minerals (Encalada et al., 2023; HBS, 2025). This connectivity also regulates the annual flood pulse, which is essential for the survival of many aquatic and terrestrial species, sustaining aquatic primary production, fish, and other biological production in the region (Science Panel for the Amazon, 2021; Zhang et al., 2024). Historically, the basin is characterized by high precipitation rates, averaging 2200 mm/year (Marengo et al., 2018; Zanin et al., 2024) and an evapotranspiration rate of approximately 1000–1500 mm/year, contributing to regional precipitation patterns (Dominguez et al., 2022).

Occurrence data of the species

The occurrence records of *P. brachypomus* (pairs of longitude and latitude that represent the specific local where a given specimen was recorded) were obtained from the AmazonFISH database (https://freshwaterfishdata-dev.ird.fr/neotropical). The occurrence records were revised in order to check for possible discrepancies in distributional data. The CoordinateCleaner package (Zizka et al., 2019) was used to identify and remove records of coordinates corresponding to capitals, country centroids, duplicated data, research institutions, and invalid coordinates. After this process, 162 pairs of geographic coordinates remained, which were mapped on a regular grid covering the Amazon basin river network provided by the HydroSHEDS database (https://www.hydrosheds.org/products/hydrorivers—Lehner & Grill, 2013) at a spatial resolution of 7 km (40,222 cells) using the EPSG 6933, an equivalent spatial reference system that keeps the area of each cell constant. When more than one record was detected in the same cell, we kept only one of them to avoid spatial autocorrelation.

Bioclimatic and hydrological variables.

The species distribution was modeled as a function of bioclimatic and hydrological variables covering the Amazon hydrographic network. Nineteen bioclimatic variables (BIO1 to BIO19) for the present and future (2050 and 2090) were taken from the WorldClim 2.1 database (http://www.worldclim.org/) with 2.5 arc minutes of spatial resolution (Fick & Hijmans, 2017). Future climate scenarios and models available in

WorldClim were provided by the Intergovernmental Panel on Climate Change's Sixth Assessment Report (IPCC-AR6; https://www.ipcc.ch/assessment-report/ar6/) considering the new Coupled Model Inter-comparison Project phase 6 (CMIP6). Future forecasts were based on two Shared Socio-economic Pathways (SSPs), one moderate (SSP2-4.5) and one pessimistic (SSP5-8.5).

Projections for different future periods and carbon emission scenarios were obtained from Atmospheric–Ocean General Circulation Models (AOGCMs) that are representative of groups with distinct climatic characteristics. The selection of AOGCMs was carried out using the chooseGCM package (Esser et al., 2025), performed in R software (R Core Team, 2022). The package performs a K-means clustering analysis to group AOGCMs based on their historical climate similarity. It then identifies the models closest to the centroid of each cluster, resulting in the selection of AOGCMs that best represent the climatic variability within each group. This approach allows studies to have predictions similar to the use of the whole set of AOGCMs available, but using only a fraction of them. Based on this analysis, four representative AOGCMs were selected and used to generate projections under both SSP2–4.5 and SSP5–8.5 scenarios: CanESM5-CanOE (Canadian Ocean Ecosystem model), GISS-E2-1-G (National Aeronautics and Space Administration—NASA, Goddard Institute for Space Studies climate model), MRI-ESM2-0 (The Meteorological Research Institute) and UKESM1-0-LL (The UK Earth System Modelling Project—UKESM).

We also used seven hydrological variables obtained from the HydroSHEDS database (https://www.hydrosheds.org/products/hydrorivers—Lehner & Grill, 2013). Bioclimatic (BIO1 to BIO19) and hydrological (referred to as climatic-environmental variables) were rescaled to a 7 km grid in order to generate current and future environmental layers used in the modeling of the species' potential distribution. Hydrological variables were assumed constant over time fovariables were rescaled to a 7 km grid in order to generate current and future environmental layers used in the modeling of the species' potential distribution. Hydrological variables were assumed constant over time for future forecasts. Multicollinearity within the set of bioclimatic and hydrological variables was evaluated using the Variance Inflation Factor (VIF). Using the usdm package in R (Naimi & Araújo, 2016), pairs of variables with the highest linear correlations were identified, and variables with the highest VIF values were iteratively excluded until the maximum correlation was reduced to 0.5. Based on these criteria, we retained BIO3 (Isothermality), BIO5 (Max Temperature of Warmest Month), and BIO8 (Mean Temperature of Wettest Quarter), among the bioclimatic variables, and DIST_DN_KM (distance from the reach outlet to the most upstream point in the river network, in km), LENGTH_KM (length of the river reach segment, in km), and ORD_STR (river order according to the Strahler method; Strahler, 1957), among the hydrological variables. These variables represent important predictors of *P. brachypomus* distribution, as they reflect climatic–environmental gradients that directly influence physiological and behavioral processes essential to the species. Thermal conditions (BIO3, BIO5, BIO8) act as reproductive triggers, regulating gonadal maturation and the onset of spawning (Vazzoler, 1996). In turn, spatial attributes of the river network (DIST_DN_KM, LENGTH_KM, ORD_STR) may be key for accessing feeding and shelter habitats, as well as influencing the viability of long-distance migrations that characterize the species' life cycle (see Correa et al., 2015; Barthem et al., 2017).

Generation of pseudo-absence and background data

Considering the non-existence of absence data of the species, we generated pseudo-absences or background points according to the requirements of each modeling algorithm. Both types of data were generated in a number equivalent to the occurrence records, in order to maintain class balance and ensure comparability across modeling approaches (Japkowicz & Stephen, 2002). For algorithms that require binary presence/absence data (GLM, RF, and SVM), pseudo-absences were randomly selected within the study area, outside an envelope defined by the environmental space occupied by the presence records (i.e., a Surface Range Envelope). This strategy ensures that pseudo-absences are distinguishable from presences in both geographic and environmental terms (Lobo et al., 2006). For presence-background models (MaxLike), background points were randomly sampled across the entire study area, without being considered true absences. These background points were treated separately from pseudo-absences throughout the modeling workflow. Finally, a binary matrix was constructed for each algorithm: presence (1) and pseudo-absence (0) for presence–absence models, and presence (1) and background (0) for presence-background models.

Ecological niche modeling

We used the binary matrices of presence and pseudo-absence and environmental layers corresponding to the set of non-collinear variables (based on VIF results) to calibrate ecological niche models (ENMs). Since different ENMs often yield divergent predictions, making it challenging to determine the most accurate representation of the species distribution (Diniz-Filho et al., 2010). In view of this, we used the ensemble forecasting approach (Araújo & New, 2007). One of the primary benefits of ensemble forecasting is the ability to combine predictions from multiple algorithms in a consensus model, thus reducing the uncertainty inherent in individual model outputs and minimizing biases or errors that might be introduced by any single model, leading to more robust and reliable predictions (Terribile et al., 2010).

In this context, we used five conceptually and statistically distinct algorithms, representing different methodological categories: regression-based models (Generalized Linear Models—GLM; Generalized Additive Models—GAM), classification (Flexible Discriminant Analysis—FDA), machine learning (Support Vector Machine—SVM; maximum likelihood estimation—MaxLike). These models were applied to estimate the suitable areas for the occurrence of *P. brachypomus* in the Amazon basin and to generate the consensus models. For conceptual underpinnings and methodological details of the algorithms used, see Drake et al. (2006), Elith et al. (2006), Franklin (2010), and Royle et al. (2012). For each algorithm, *P. brachypomus* occurrence data were randomly divided into two datasets. One, comprising 75% of the data, was used for calibration and the other, with 25%, for model evaluation. This process was repeated 10 times using a cross-validation system of subsampling K-folds, with $K = 4$ (totalizing 40 repetitions). In this procedure, the dataset is divided into K equally sized subsets or ''folds.'' The model is then trained and tested K times, with each fold serving as the testing set once, while the remaining K-1 folds are used for training (Naime & Araújo, 2016). This process ensures that each data point is used for both training and testing, which provides a more reliable estimate of model performance.

Based on this approach, we obtained 40 suitability projections per algorithm. To standardize the outputs, each projection was converted into a binary presence-absence map using the threshold that maximizes the sum of sensitivity and specificity (Liu et al., 2016). For each grid cell, we then calculated the proportion of times the species was predicted as present across the 40 repetitions of each algorithm. This frequency value, ranging from 0 to 1, represents the proportion of repetitions in which the species was predicted as present in each cell and was adopted as a standardized measure of suitability for model comparison. We summed the binary outputs and divided the result by the number of presences, generating the frequency outputs that represent comparable suitability among different models. Thus, for each cell, the comparable suitability (i.e., the frequency) was calculated, ranging between 0 and 1 (1 represents the most suitable conditions and 0 represents unsuitable conditions). Climatic-environmental suitability was then converted in presence and absence to obtain the species distribution, where values higher than 0.5 represented presences, and values lower than or equal to 0.5 represented absences (Hirzel et al., 2006; Stuart et al., 2021).

The predictive performance of ENMs for projection was evaluated using the Receiver Operating Characteristic (ROC) method, which generates a curve in a bivariate space by plotting the true positive rate (sensitivity) against the false positive rate (1—true negative rate or 1—specificity). This evaluation technique involved multiple sorts of modeled presence-absence outputs using various threshold settings to create confusion matrices. The Area Under the Curve ROC (AUC) was calculated as a measure of the predictive performance of models, independent of the decision threshold (Manel et al., 2001; Liu et al., 2005). AUC values of 0.5 indicate models that perform no better than a random selection, while values close to 1 indicate very good performance with high true-positive rates and low false-positive rates. Models with $AUC > 0.8$ were combined to obtain a consensus prediction (Araújo & New, 2007). Consensus models were generated using the majority consensus rule (adapted from

Diniz-Filho et al., 2009) which considers species presence only in cells where more than 50% of the retained model in the ensemble indicated the species as being present. Figure 1 the climatic-environmental suitability of the consensus was then calculated as the mean suitability of the retained models. The modeling protocol generated a total of 200 projections for the current time (5 algorithms × 40 repetitions) and 3,200 projections for the future scenarios (5 algorithms × 40 repetitions × 4 climate models × 2 SSPs × 2 future times).

Using the presence and absence data estimated by the consensus model, we assessed the projected changes in the distribution of *P. brachypomus* in response to climate change in the Amazon Basin. For that, we quantified the number of cells occupied by the species as well as the losses and gains in each sub-basin and calculated the percentage of variation in its distribution area, considering the years 2050 and 2090 and under the SSP2-4.5 (moderate) and SSP5-8.5 (pessimistic) scenarios. This approach allowed us to identify the main sub-basins that are likely to be impacted by the decline of *P. brachypomus* populations and those that tend to sustain the species' populations in the long run.

Geoprocessing, variable selection and ecological niche modeling were performed in R software (R Core Team, 2022) using a tailor-made script (available at https://github.com/luizesser/Piaractus) based on the *sdm* package (Naimi & Araújo, 2016). Maps were produced using QGIS 3.40.1.

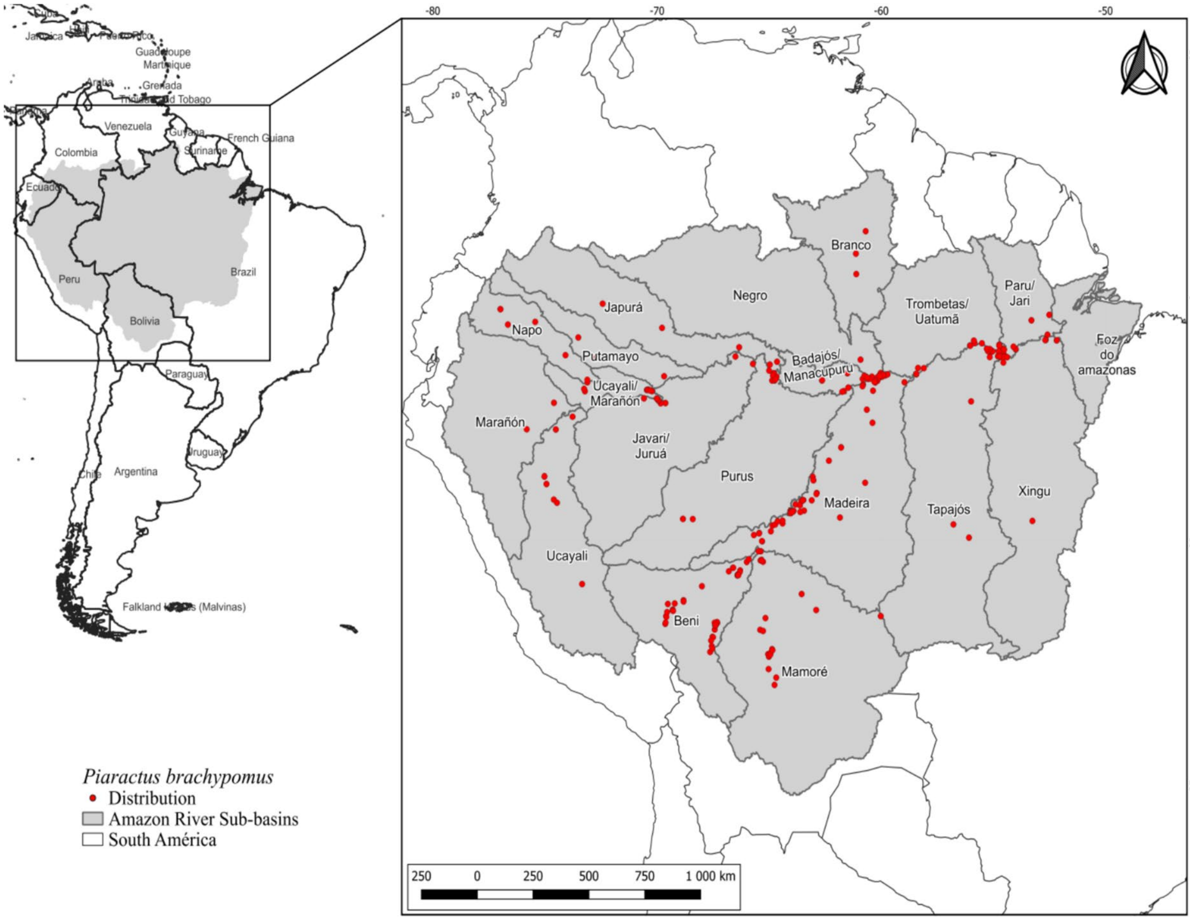

Fig. 1 Observed occurrences records of *Piaractus brachypomus* distributed in the Amazon sub-basins

Results

The consensus model showed high predictive performance, with a mean AUC of 0.94 ± 0.02 SD. Predictions for the current time indicate that the Amazon basin exhibits high environmental-climatic suitability for *P. brachypomus*, particularly in the southwestern region and central Amazonia. Tributaries located in the western (southern Colombia and northern Peru), southern (central-northern Bolivia and a little portion of southeastern Peru), and eastern (mouth of the Amazon River) regions also proved favorable for the occurrence of the species. In these areas, the rivers Caquetá (Colombia), Putumayo (Colombia-Peru border), Ucayali and Marañón (northern Peru), Madre de Dios (Bolivia), the drainage of the Negro, Japurá, and Branco rivers, to the north, and stretches of the Madeira, Purus, and Tapajós rivers, to the south (Central Amazonia, Brazil), showed high climatic favorability for the species (Fig. 2a–b; Online Resource 1).

Future projections indicate a decline in suitable areas for *P. brachypomus* across the Amazon basin (Fig. 3). For 2050, in the moderate climate scenario, a minor decrease in these areas is expected, primarily in the rivers of the northern and southern regions of the basin, with the highest environmental-climatic suitability the southwestern region. The same trend is expected in both the pessimistic and the moderate scenarios for 2090 (Fig. 3a–c). Losses are expected to increase by 2090 under the pessimistic scenario, particularly in the tributaries of the large rivers of the Amazon basin. In contrast, some rivers in the southwestern and central regions, including the main channel of the Amazon River, are projected to maintain favorable environmental-climatic conditions for the occurrence of *P. brachypomus* by the end of the twenty-first century (Fig. 3d).

Based on the distribution estimates of *P. brachypomus* in the Amazon basin, 11 of the 19 sub-basins are expected to maintain suitable areas for the occurrence of the species in 2050 and 2090 (only in the moderate scenario). On the other hand, in the Branco, Negro, and Mamoré sub-basins, the species is predicted to lose approximately 60% of the current suitable areas. Still, a more pronounced contraction in the distribution area of *P. brachypomus* is predicted for 2090 under the pessimistic scenario across all sub-basins, including the three aforementioned, as well as Japurá and Purus, where losses may exceed 90% of the currently estimated distribution. Gains in suitable areas were predicted mainly for the Xingu subbasin in 2050 (moderate and pessimistic scenarios) and in 2090 (moderate scenario), and sparingly predicted for Foz do Amazonas, Japurá, Napo, Putamayo, and Ucayali subbasins only for the moderate scenario in 2050 (Fig. 4a–d; Fig. 5).

Discussion

Our projections showed that climate change will trigger range contractions of *P. brachypomus* in the

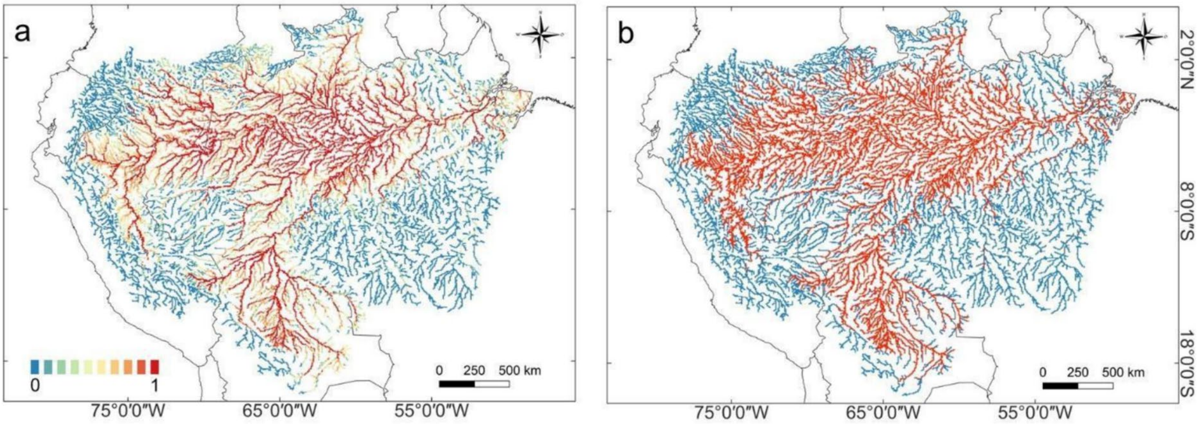

Fig. 2 Environmental-climatic suitability **a** and presence/absence **b** estimated for *Piaractus brachypomus* in the Amazon basin for the present. In **b**, presence is indicated by red cells and absence by blue cells. Estimates are based on the results of the consensus models

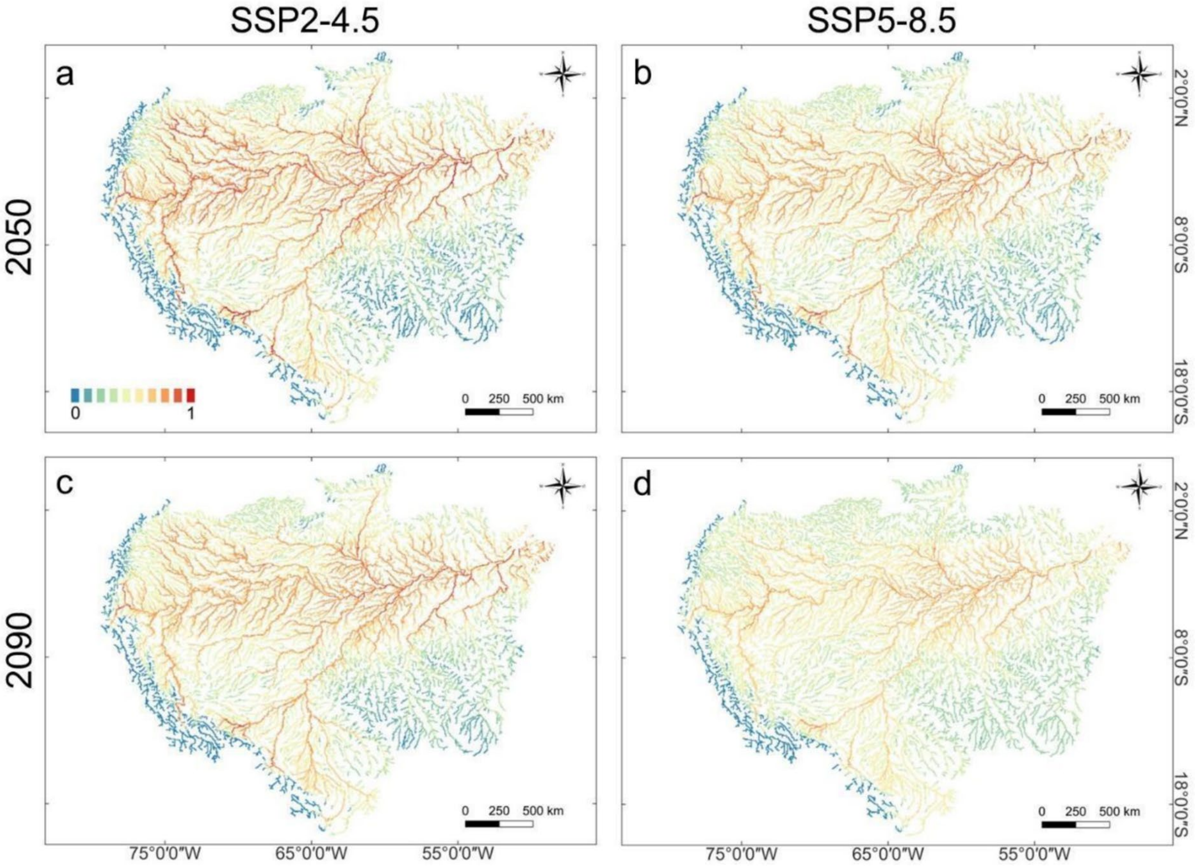

Fig. 3 Environmental-climatic suitability estimated for *Piaractus brachypomus* in the Amazon Basin for 2050 and 2090 under climate change scenarios SSP2-4.5 (moderate) and SSP5-8.5 (pessimistic)

Amazon basin, particularly under a pessimistic scenario. Although currently "pirapitinga" is a widespread species in the Amazon, the results of our study indicate that by the end of the century, there could be expressive losses of suitable areas for its potential distribution. In addition, the predictions revealed that at the current time nearly half of the Amazon basin presents favorable environmental conditions to support the widespread distribution of *P. brachypomus*. This is especially relevant given that *P. brachypomus* is a migratory species that performs longitudinal and lateral migrations, connecting distinct biotopes to complete its life cycle (Correa et al., 2015; Barthem et al., 2017; Herrera-R et al., 2023). Thus, the current availability of large and continuous areas of suitable conditions in the main rivers of the basin favors the species' displacement across large portions of the Amazon.

The future rearrangement of environmental conditions can elicit distinct responses from fish fauna, leading to either range expansion or contraction. Range contraction was the general predicted trend for "pirapitinga", although moderate and limited expansion was also forecasted in Xingu and Foz do Amazonas, Japurá, Napo, Putamayo, and Ucayali subbasins, respectively. These antagonic responses can result from the fact that species have specific environmental requirements, especially those related to climate, which can either restrict or expand their presence to areas where physiological and ecological constraints are minimized (Val & Wood, 2022). Where conditions were predicted to remain tolerable, resilience of some sub-basins in the southwestern could afford range expansion of "pirapitinga" on the assumption that Amazon fishes are effective dispersers and can track favorable conditions in the future (Oberdorff

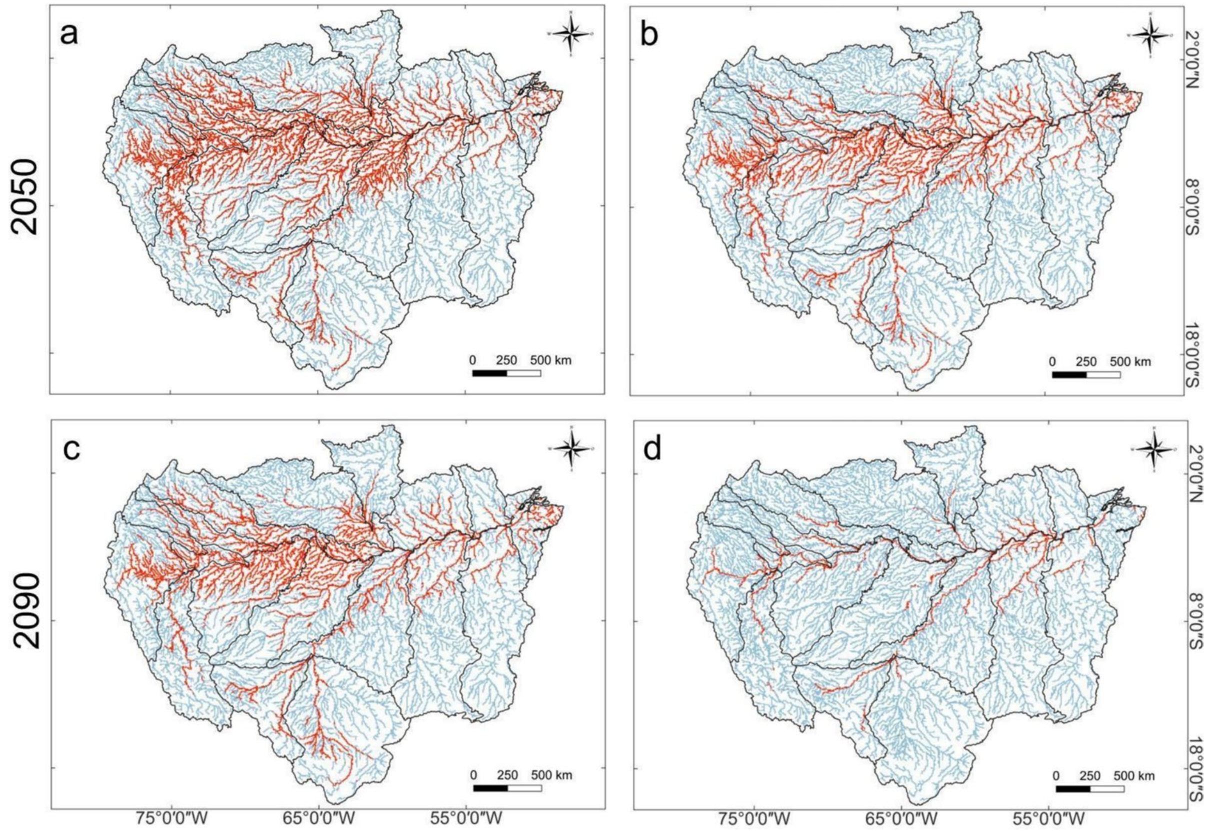

Fig. 4 Presence/absence estimated for *Piaractus brachypomus* in Amazon sub-basins for the years 2050 and 2090, under climate change scenarios SSP2-4.5 (moderate) and SSP5-8.5 (pessimistic). Presence is indicated by red cells and absence by blue cells. Estimates are based on consensus models

et al., 2016). However, if the suite of environmental conditions surpasses the species' tolerance limit, populations are unable to persist in the longer term (Ficke et al., 2007; Mee et al., 2018), and these areas previously suitable for the species may become environmentally unfavorable. In this sense, it is important to emphasize that even in the sub-basins projected to experience range expansion, including Xingu, the species is projected to completely lose the suitable conditions for its occurrence in more distant time periods and harsher climatic conditions (pessimistic scenario).

While most available studies support the idea that range contraction is the likely response of cold-water species to changes in climate (Comte et al., 2013), tropical fish living in seasonal environments like *P. brachypomus* may also have their ranges contracted. Many tropical species are expected to be vulnerable to extreme temperatures, as they already live at their upper thermal limits and acclimatization may be limited (Pörtner & Farrel, 2008; Barletta et al., 2010; Lapointe et al., 2018). Even small increases in temperature could be exacerbated by other stressors, such as hypoxia, through additive or synergistic effects (Campos et al., 2019; Jung et al., 2020; Braz-Mota & Val, 2024). Precipitation can also be a critical driver for fish living in seasonal environments, determining population persistence under shifting rainfall and drought conditions.

According to our projections, *P. brachypomus* is likely to experience progressive range contraction, starting with less dramatic decreases in northern and southern tributaries by 2050. By 2090, northern regions (mainly Branco and Negro sub-basins) will continue to lose substantial suitable areas and several tributaries will also become unsuitable, as is the case of Japurá, Mamoré, and Purus that are expected to lose more than 90% of their suitable areas under

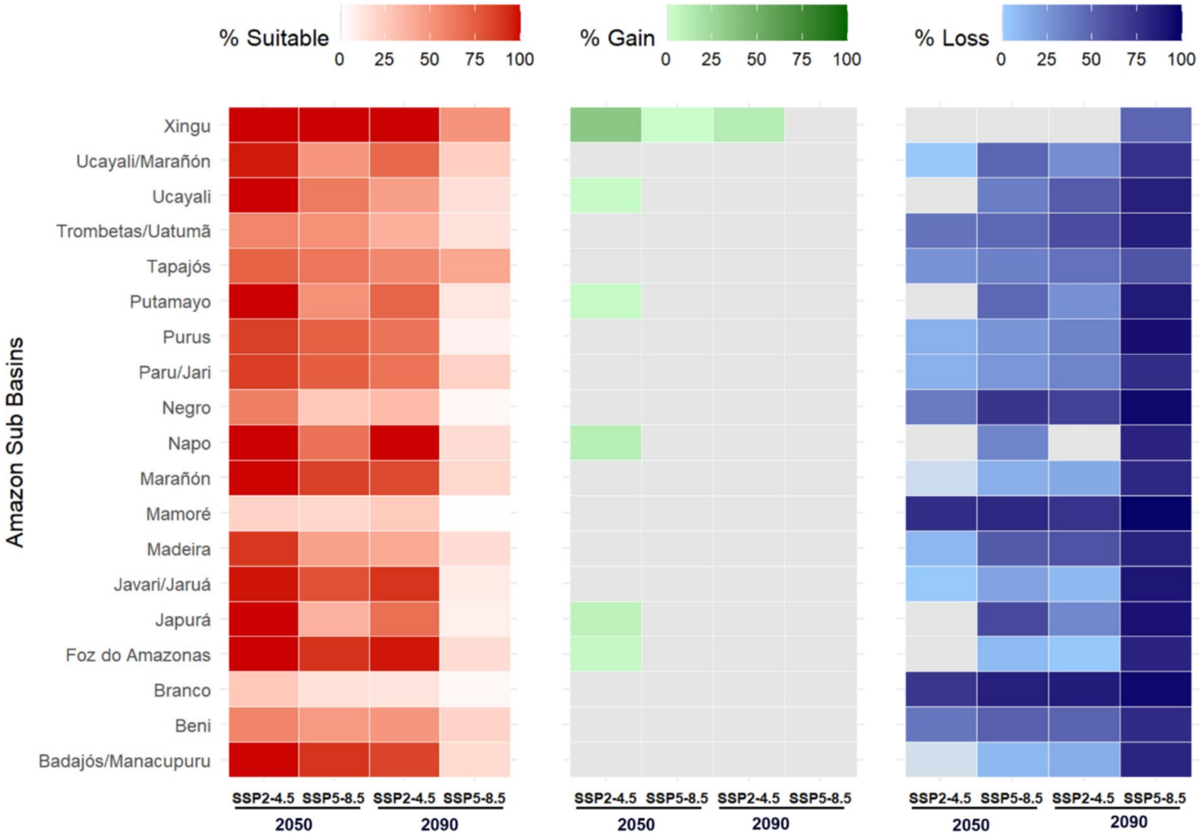

Fig. 5 Percentage of climatically suitable areas, gains, and losses over time for *Piaractus brachypomus* in the Amazon sub-basins under different climate change scenarios. The color gradient—red (highly suitable), green (gain) and blue (high loss)—represent changes in environmental conditions projected for 2050 and 2090 under SSP2-4.5 (moderate) and SSP5-8.5 (pessimistic) scenarios

the pessimistic scenario. Northeastern regions are projected to undergo increasingly longer dry seasons with decreased annual precipitation (Duffy et al., 2015; Sorribas et al., 2016; Bottino et al., 2024). If drier conditions prevail, then the decreased river discharges as well as low water periods could reduce the extent of floodplain habitats and contiguous river channels, compromising the dispersal corridors between critical habitats (Duponchelle et al., 2021; Röpke et al., 2022). In the case of the frugivorous *P. brachypomus*, lateral migrations to flooded forests are closely tied to the tree's fruiting periods with the high-water season (Lucas, 2008; Correa et al., 2015). Several fish in the Amazon accumulate a surplus of energy during periods of high availability of resources, which will sustain individuals over the low-water periods (Röpke et al., 2019). However, given that prolonged droughts are projected for the area (Duffy et al., 2015), the flooded forests are expected to contract, reducing both the survival and reproductive success of *P. brachypomus*.

This can also reverberate across ecological networks, threatening plant-fish interactions, especially seed dispersal, an ecological process essential for provisioning ecosystem services, in which *P. brachypomus* is highly effective (Anderson et al., 2009). By dispersing seeds of a large number of plants, *P. brachypomus* affects regional plant composition and diversity along lowland rivers (Correa et al., 2015). In southeast areas, namely the arc of deforestation (Coe et al., 2013; Montibeller et al., 2020), where forests are predicted to be impacted by increased warming and low resilience (Staal et al., 2015; Flores et al., 2024) the decline of *P. brachypomus* populations and loss of suitable areas can impact forest diversity and survival. Beyond ecological implications, socioeconomic effects can also be anticipated. *Piaractus brachypomus* is an important species for commercial fishing, aquaculture, and subsistence (Santos et al., 2009; Goulding et al., 2018; Dias et al., 2023). The loss of environmentally suitable areas may reduce fish stocks, directly affecting fishery productivity and compromising the livelihoods of local populations, potentially exacerbating existing socioeconomic inequalities in the region. Although under the high-emission scenario we found a trend of decreasing suitable habitat for the species, we should highlight that most sub-basins are predicted to retain climatically stable areas at least under the moderate scenario. These projections can represent a middle ground pathway rather than only the worst case scenario, which makes climate adaptation strategies more feasible for policymakers rather than impossible (Hausfather & Peters, 2020; Pielke & Ritchie, 2021; Burgess et al., 2023). Pointing out the less dramatic scenario does not make climate actions less urgent; on the contrary, it highlights the urgency of effective measures to mitigate more severe future scenarios. In fact, it emphasizes the importance of meeting the Paris Agreement targets, since doing so could result in retaining as much suitable habitat as possible by the end of the century. To secure suitable habitats for *P. brachypomus*, cross-border actions must take place. Countries that share the Amazon basin must collaborate on unified approaches to mitigate the worst effects of climate change (Tigre, 2019), regulating drivers such as hydropower expansion (Flecker et al., 2022), cattle ranching and agribusiness with environmental protection. Cooperation among countries can enhance their position on international climate diplomacy, securing funding and support to protect shared ecosystems and livelihoods (Paes, 2022).

Although this study focused on *P. brachypomus*, its ecological traits, such as long-distance migration and frugivory, are shared with other important Amazonian genera, including *Colossoma*, *Mylossoma*, and *Brycon*. These genera comprise a functional guild of frugivorous and migratory fishes that play a key role in seed dispersal and forest regeneration (Anderson et al., 2009; Correa et al., 2015). Given these ecological similarities, the climate-driven shifts projected for *P. brachypomus* may be representative of changes affecting other species within the same guild. Building on this, predicting regions where species can persist under moderate or extreme climate changes are key components of climate adaptation strategies (Morelli et al., 2020). If the risk from climate change arises mostly associated with reduced precipitation and lengthening of the dry season (Marengo et al., 2018; Gatti et al., 2021), then areas with highest rainfall and flattened seasonality (Killeen & Solórzano, 2008) should maintain favorable conditions in future scenarios. For instance, the main channel of the Amazon River and, primarily, the Beni, Javari/Jaruá, Madeira, Marañón, and Tapajós were sub-basins predicted to retain most persistent occupied cells across the scenarios, which can put *P. brachypomus* populations on the 'slow lane' of the physiological stress of climate change.

The future projections of increased precipitation and duration of flooding in the western region (Sorribas et al., 2016; Carvalho et al., 2020; Gedney et al., 2024) could mitigate some negative effects of the overall trend of severe and frequent droughts projected for the end of the century (see Duffy et al., 2015). In the Central Amazon, the large river channels are expected to maintain suitable conditions for *P. brachypomus*, as the occurrence of this species, like other lotic environment specialist species, is closely predicted by high order streams and their floodplains (Ruaro et al., 2019). Therefore, the preservation of these areas will be essential for maintaining *P. brachypomus* populations and, should climate conditions become favorable again, enabling the occupation of new areas within the basin.

Conclusion

The predicted loss and reduction of suitable areas for the frugivore *P. brachypomu*s in the future signals the urgent need for conservation and management actions towards aquatic ecosystems. Beyond climatic-environmental variables, the maintenance of amazonian fish stocks relies on water quality and quantity, and river connectivity, which are affected by unprecedented environmental pressures, including deforestation, mining, illegal fires and hydropower expansion, compromising the ability of *P. brachypomus* to track suitable areas. The loss of suitable areas, especially under the pessimistic scenario, underscore the urgency of protecting free-flowing rivers and identifying climatically stable sub-basins, which should be prioritized for conservation actions as they are likely to support populations in the facing of rising temperatures and lengthening of dry seasons.

Beyond the species itself, the disruption of seed dispersal could have cascading effects on Amazon biodiversity, especially at southeast regions where forest resilience is already at risk. While there are national fishery management policies in place in the regions where this species occurs, many of these policies remain unclear, poorly enforced or insufficient to meet their conservation goals. Countries sharing the Amazon basin must coordinate a policy framework to ensure the persistence of this frugivore migratory fish. This requires restricting further degradation of high-quality habitats and promoting conservation efforts to reverse degraded environments, explicitly accounting to buffer the foreseeable effects of climate change on the freshwater realm, to safeguard both biodiversity and the human communities that rely on *P. brachypomus* as income and protein source.

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Data availability Data will be made available upon request.

Declarations

Conflict of interest The authors declare that they have no conflicts of interest.

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