

Conservation status and spatiotemporal distribution of fish with socioeconomic importance in the Amazonia-Cerrado transition zone

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ABSTRACT

On the southern edge of Brazilian Amazonia, within the Araguaia-Tocantins Basin, the Araguaia River and its main tributary, the Mortes River, are of high ecological, geopolitical and socioeconomic importance. Understanding the effect of climate on fish distribution is vital for sustainable resource management. We aimed to apply spatiotemporal distribution models for a past (Last Glacial Maximum, LGM), current and future climate scenario for the most fished and commercially relevant fish species in the Mortes River Basin. The species with the highest fishing frequencies were *Pseudoplatystoma fasciatum* (90%), *Brycon falcatus* (74%), *Myloplus torquatus* (68%) and *Leporinus friderici* (39%). The environmental variables that best explained the spatial distribution of these species were altitude, temperature, and precipitation. Our projections revealed that all species had extensive areas of continuous and connected environmental suitability niches (ESNs) during the LGM. The current geographic distribution of the species is determined by environmental conditions, however, the predicted ESNs overlap with areas under intense agricultural exploitation. In a pessimistic future scenario, with increase in temperatures, *B. falcatus* and *P. fasciatum* could disappear, while *M. torquatus* and *L. friderici* could adapt by modifying their ESNs. Currently, the protected areas in the studied basin do not adequately represent the habitats with higher environmental suitability for the occurrence of these species. More effective initiatives to protect and manage fishery resources are needed in the Araguaia-Tocantins and Mortes basins to allow for sustainable conservation policies.

KEYWORDS: environmental suitability, ichthyofauna, altitude, temperature, climate change, *Pseudoplatystoma fasciatum*

Estado de conservação e distribuição espaço-temporal de peixes de importância socioeconômica na zona de transição Amazônia-Cerrado

RESUMO

No extremo sul da Amazônia brasileira, na Bacia Araguaia-Tocantins, o Rio Araguaia e seu principal afluente, o Rio das Mortes, são de grande importância do ponto de vista ecológico, geopolítico e socioeconômico. Entender o efeito do clima na distribuição de peixes é vital para o gerenciamento sustentável de recursos. Nosso objetivo foi aplicar modelos de distribuição espaço-temporal para um cenário climático passado (Último Máximo Glacial, LGM), atual e futuro para as espécies de peixes mais pescadas e comercialmente relevantes no Rio das Mortes. As espécies com maiores frequências de pesca foram *Pseudoplatystoma fasciatum* (90%), *Brycon falcatus* (74%), *Myloplus torquatus* (68%) e *Leporinus friderici* (39%). As variáveis ambientais que melhor explicaram a distribuição espacial dessas espécies foram altitude, temperatura e precipitação. Nossas projeções revelaram que todas as espécies apresentaram extensas áreas de adequação ambiental (ESNs) contínuas e conectadas durante o LGM. A distribuição geográfica atual das espécies é determinada pelas condições ambientais; no entanto, as ESNs previstas sobrepõem-se a áreas sob intensa exploração agrícola. Em um cenário pessimista futuro, de aumento nas temperaturas, *B. falcatus* e *P. fasciatum* poderão desaparecer, enquanto *M. torquatus* e *L. friderici* poderão se adaptar modificando seus ESNs. Atualmente, as áreas protegidas da bacia estudada não representam adequadamente os habitats com maior adequação ambiental para a ocorrência destas espécies. Iniciativas mais eficazes para proteger e gerenciar os recursos pesqueiros são necessárias nas bacias Araguaia-Tocantins e das Mortes para permitir políticas de conservação sustentáveis.

PALAVRAS-CHAVE: adequação ambiental, ictiofauna, altitude, temperatura, mudanças climáticas, *Pseudoplatystoma fasciatum*

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INTRODUCTION

The Amazon Basin is the largest river basin in the world, covering over six million km² and housing ~2,500 validated native freshwater fish species (Jézéquel *et al.* 2020). The Araguaia-Tocantins Basin, despite being considered a separate drainage system, is connected with the Amazon Basin and its biota is related to the latter by historical processes (Farias *et al.* 2019) and also houses a high fish biodiversity (Latrubesse *et al.* 2019). The Mortes River (*Rio das Mortes*, in Portuguese) is the main tributary of the Araguaia River, and is one of the most extensive and biodiverse rivers in Mato Grosso state, Brazil (Lima *et al.* 2021). The Araguaia and Mortes rivers form the largest floodable area in Brazil, the Bananal Sedimentary Plain, located in the transition between the two largest neotropical biomes, Amazonia and Cerrado (Martini 2006) and one of Brazil's RAMSAR wetland sites (Araguaia National Park - *Ilha do Bananal*) (<https://www.ramsar.org/country-profile/brazil>) (MMA 2023a). The sedimentary plain overlaps with the extensive “arc of deforestation”, the south-southwestern rim of the Amazon region undergoing the most intense anthropic impacts (Latrubesse *et al.* 2019; Pelicice *et al.* 2021), and has been undergoing extreme drought and flood events due to environmental and climatic changes, which compromise the ecophysiology of fish, disrupt reproductive patterns, and reduce fishing productivity, affecting local food security (Plagányi 2019).

The Mortes River Basin is a priority area for the conservation of the southern Amazonian aquatic biota (Nogueira *et al.* 2010) due to the importance of its wetlands and the high impact level it sustains. The Mortes River drains into agricultural areas under intensive livestock farming and large-scale monocultures. Yet ~25% of its length runs through indigenous lands (Rosin *et al.* 2015), which confers a degree of environmental protection. Safeguarding the ecological integrity of this river is thus critical for biodiversity conservation and the food security of traditional riverside communities by adopting sustainable fishing practices (Matos *et al.* 2020).

The Mortes River also is home to a rich ichthyofauna sustained by varied and connected habitats that are essential for feeding, sheltering and reproduction of species (Melo *et al.* 2005; Borges 2018), and many species are of great economic and cultural importance (Melo *et al.* 2005; Lima *et al.* 2021). The flooding dynamics and connection with the Araguaia River ensure the maintenance of biodiversity and sustain activities such as subsistence and sport fishing, which generate income and food for riverside communities (Melo *et al.* 2015). However, overfishing, combined with agricultural expansion and environmental degradation are a growing threat to fish stocks in these rivers (Nogueira *et al.* 2010; Zacarkim *et al.* 2015; Lima *et al.* 2021).

Species distribution models are an important analytical tool for evaluation of the effect of climate and environmental

changes, as well as the uncertainties about biota conservation, on the spatiotemporal distribution patterns of biodiversity (Paglia *et al.* 2012; Alvarez *et al.* 2021), especially concerning Amazonian fish (Alvarez *et al.* 2020). These models enable the prediction of environmental suitability niches, offering insights into spatial trends under climate change scenarios and guiding the development of effective conservation plans for ecosystems and vulnerable species (Paglia *et al.* 2012). Predicting past, current or future species distributions using bioclimatic models may assume that climate has constrained species distributions, identifies the potential distribution of species, and assesses whether current distribution areas will remain suitable under future climate scenarios (Beaumont *et al.* 2005; Alvarez *et al.* 2021).

In this study, we evaluated the distribution in past, present and projected future climatic scenarios, as well as the protection level awarded by current conservation areas to focal fish species in the Araguaia-Tocantins Basin. We placed special emphasis on the Mortes River sub-basin, due to its environmental relevance and socioeconomical importance for traditional communities. We constructed models to estimate the distribution patterns under past, current and future scenarios of the four most fished species in the Mortes River Basin, aimed at answering the questions: i) what are the environmental variables that best explain the current spatial distribution of the target species?; ii) what are the historical (past and current) and predicted future distribution patterns of these species?; and iii) the suitable ecological niches of these species are covered by the current protected areas in the Araguaia-Tocantins basin? Considering the known relationship between rainfall and hydrological connectivity (Dias *et al.* 2025), we hypothesized that precipitation would be one of the variables with the greatest effect on the distribution of our target species. Given the biogeographic history of the species (Lowe-McConnell 2012), we also expected that their distribution would be wider in the past and that those species sensitive to climate change would experience reduction and displacement of their environmental suitability. Finally, considering that environmental policies are generally linked to economic and political interests, we expected to obtain a low overlap between species distribution predictions and currently existing protected areas (Stewart *et al.* 2022).

MATERIAL AND METHODS

Study area and fish data collection

The Araguaia-Tocantins Basin is the second largest hydrographic basin in Brazil with ~780,000 km². Both the Tocantins and Araguaia rivers, carry a high volume of water and experience, as all Amazonian rivers in general, seasonal flood pulses (Latrubesse *et al.* 2019). The regional climate is classified as Köppen's savanna subtype Aw, with a rainy summer from October to April, and a dry winter from May

to September (Alvares *et al.* 2013). The original vegetation is characterized by savannah formations and riparian forests of the Cerrado Biome (Marimon *et al.* 2012).

The watershed of the Mortes River covers ~61,000 km² (Rosin *et al.* 2015). It rises in the São Jerônimo highlands (*Serra de São Jerônimo*, Mato Grosso state) and mounds into the Araguaia River in the municipality of São Félix do Araguaia, within the Bananal floodplain, also in Mato Grosso. The average annual rainfall in the Mortes Basin is around 1,600 mm, with the highest intensity between December and February; and the average annual temperature is ~25 °C (Marimon *et al.* 2012). The Mortes Basin is ethnoculturally rich, including seven important indigenous territories, as well as strategic conservation units, such as the Araguaia State Park (Coimbra-Junior *et al.* 2004; Marimon *et al.* 2012).

The local economy is based on agriculture, livestock and tourism, while the riverside communities along the Mortes River rely mainly on artisanal fishing for their livelihood (Zacarkim *et al.* 2015). Data on the most fished, consumed, and marketed fish species in the Mortes River were collected from riverside fishermen of the Colony of Fishermen Z-09 in the municipalities of Nova Xavantina, Nova Nazaré and Novo Santo Antônio (Figure 1). In 2023, there were 80 registered professional and artisanal fishermen in these three municipalities, according to data from computerized the fishing activity registration system-SISRGP 4.0 (Brasil 2023). We conducted interviews with 105 riverside dwellers (people living along the riverbanks, whose livelihoods and routines are closely connected to the river, but who are not necessarily fishermen) and fishermen (those who live along the river and engage in fishing as a subsistence or commercial activity) to determine the four most fished, consumed and sold species. We interviewed 37 persons in Nova Xavantina, 35 in Novo Santo Antônio and 33 in Nova Nazaré. To select interviewees, we applied the Snowball sampling method (Goodman 1961), where initial participants (seeds) referred new participants, until the indications are repeated, and a network of informants is completed. During the visits and interviews, whenever a species of fish was mentioned (popular local name), we requested to see a freshly caught or refrigerated specimen and, if not available, we showed pictures and photographs to confirm species identification.

The interviews were authorized by the research ethics committee of Universidade do Estado de Mato Grosso - UNEMAT (CAAE # 25715019.0.0000.5166). Testimony material of the fish species here analysed are deposited in the ichthyological collection of the Nova Xavantina campus of UNEMAT (587/GL38, 480/GL12, 1689/GL21 and 2026/GL101).

Species distribution models

Distribution models for the four target species were created for the whole Araguaia-Tocantins Basin (Figure 1), for which

a large georeferenced database was available for each species. We compiled digitalized occurrence records from SpeciesLink (<http://splink.org.br>), Global Biodiversity Information Facility - GBIF (<http://gbif.org>) and FishBase (<http://fishbase.org>), as well as from scientific articles, and data from the ichthyological collection at UNEMAT's Nova Xavantina Campus. We extracted geospatial records from the Brazilian territory and later filtered for the Araguaia-Tocantins Basin to develop the models. To minimize sampling bias, additional occurrences within a 5-km radius area around a given occurrence were excluded, assuming similar environmental conditions in close proximity.

We used 19 climate and altitude variables, between 1970 and 2000, from the WorldClim platform (<http://worldclim.org>) with a spatial resolution of 2.5 arc-minutes (~5 km at the equator) (Hijmans *et al.* 2005), extracted for the Araguaia-Tocantins Basin. To eliminate multicollinearity, we used

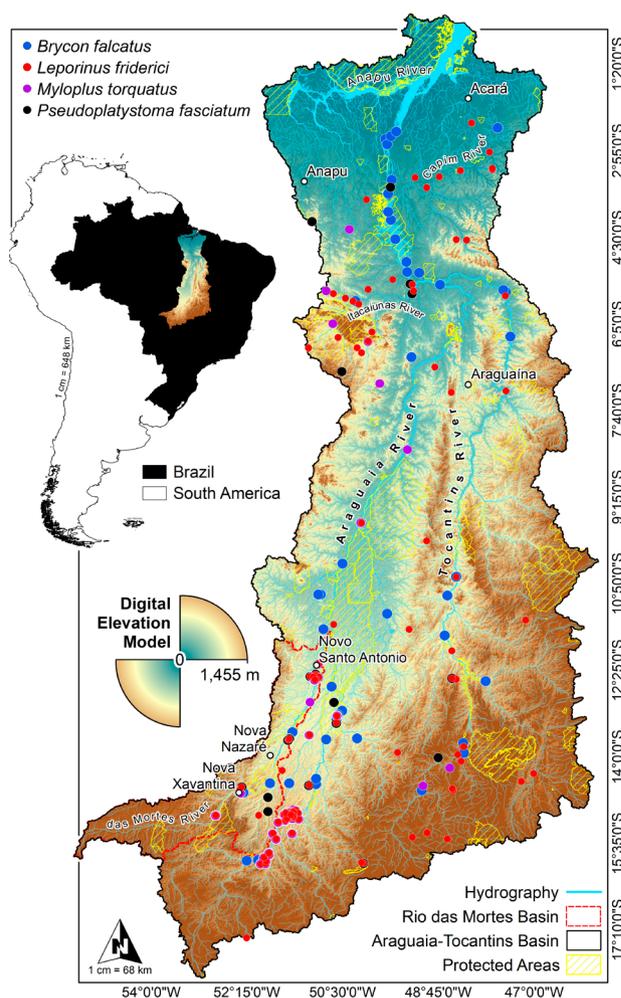


Figure 1. Occurrence records of the four target fish species in the Araguaia-Tocantins River Basin, in north-central Brazil (see inset). The three localities in the Mortes River where interview data were collected are indicated. Yellow lines indicate protected areas (conservation units and indigenous lands).

the variance inflation factor ($VIF < 5$) allowing to reduce the dimensionality of these variables, from the R 'usdm' package (Naimi 2017), and the analysis resulted in seven environmental variables without multicollinearity (Table 1). Using MaxEnt terminology, we assessed the importance of each variable for each species (Elith and Leathwick 2009).

To identify the potential effects of climate change on the spatial distribution of the species, we selected future simulations of the environmental variables under the most pessimistic climate change scenario, based on the Coupled Model Intercomparison Project (CMIP6) and Shared Socio-economic Pathway (SSP) (Eyring *et al.* 2016; Meinshausen *et al.* 2020). Using WorldClim 2.0, we selected the SSP5-8.5 "pessimistic" scenario, which projects an increase in gas emissions and a temperature rise of +8.5 °C between 2021 and 2040 (Moss *et al.* 2010) to evaluate the potential impact of climate change on the four species currently most fished in the Mortes River.

For the past projections, we used the period of the Last Glacial Maximum (LGM), ~21,000 years ago (Sato *et al.* 2021). We selected the Global Circulation Models (GCMs) that projected more extreme scenarios in terms of temperature and precipitation, and that also provided simulations for future climate conditions under the SSP5-8.5 scenario of CMIP6. We then performed a cluster analysis based on the similarity among the nine GCMs available in WorldClim 2.0 (Hijmans *et al.* 2005; Fick and Hijmans 2017). Finally, we used the Model for Interdisciplinary Research on Climate (MIROC6) to assess climate predictions and future projections (Tatebe *et al.* 2019). We adopted the same clipping and scaling procedures for the past, current and future scenarios.

To model the distribution of the four species, we applied three algorithms: MaxEnt (Phillips *et al.* 2006), GLM (Guisan *et al.* 2002) and Random Forest (Breiman 2001), using the SDM package (Naimi 2017) from R Core Team. We used two selection criteria for a balanced analysis: i) the categories proposed by Franklin (2010) (i.e., envelope and similarity, statistical/regression and machine learning); and ii) the type of data required for model calibration. We kept all algorithms at their default settings and generated the number of pseudo-absences in the same way as the number of occurrence records for algorithms that require presence and absence data. For algorithms that depend on the background, i.e., on many random occurrence records in the study area, such as MaxEnt, we used 10,000 occurrence records to represent the background. We calibrated the remaining algorithms solely with presence data and each set of pseudo-absences underwent five repetitions, resulting in 60 models for each algorithm.

Only models with True Skill Statistics (TSS) metric > 0.4 were included in subsequent analyses, as they exhibited greater discriminative ability than expected by chance (Zhang *et al.* 2015). Additionally, we applied the independent limit

of the area under the receiver-operating curve (ROC AUC) to validate the test that discriminates areas of omission from areas with known occurrence and indicates whether the model was suitable or not. For these descriptive statistics, values close to 1 indicate excellent model performance and values lower than 0.5 indicate inadequate models (Elith 2000).

We projected the models onto geographic space using the selected environmental variables for both current and future time intervals in a temperature rise of +8.5 °C scenario. To create a single map for each time interval and climate scenario, we combined the continuous maps by summing and averaging them. Subsequently, we converted the continuous maps into binary maps using a threshold that maximizes Specificity Sensitivity (Liu *et al.* 2005). As our main interest was to demonstrate potential changes in environmental suitability for the target species, we report the Last Glacial Maximum, current and future ESNs based on an ensemble model approach (Grenouillet *et al.* 2011).

Conservation status

We selected the protected areas (conservation units and indigenous lands) listed in the World Database on Protected Areas (WDPA) platform (<https://www.protectedplanet.net>) for the Araguaia-Tocantins Basin. To determine the conservation status of the target species, we used the protected areas as a cut-off mask to calculate the overlap between binary predictions of environmental suitability and protected areas. This involved extracting the number of pixels from each prediction within each protected area. Although the models obtained manage to represent the environmental suitability of the target species and overlap with their known geographic distribution, we decided to delimit the binary predictions to the hydrological network (Supplementary Material, Figure S1). To accomplish this, we used a shapefile of the regional hydrological network as the cut-off mask (see Nardi *et al.* 2019) and clipped each binary prediction by this hydrological mask using QGIS.

RESULTS

Most cited species

The species most cited by riverside communities were *Pseudoplatystoma fasciatum* (Linnaeus, 1766) (Pimelodidae), locally known as *pintado* or *cachara*, with 90% of citations in the interviews; *Brycon falcatus* Müller & Troschel, 1844 (Characidae), known as *voadeira* or *matrinxã* (74%); *Myloplus torquatus* (Kner, 1858) (Serrasalmididae), known as *pacu* (68%); and *Leporinus friderici* (Bloch, 1794) (Anostomidae), known as *piau-três-pintas* (39%).

Distribution and LGM to present transition

All species in the LGM distribution models were primarily concentrated in the southwestern and northern Araguaia-Tocantins Basin, coinciding with area of the Mortes River

watershed in the southwest (Figure 2). The ESN areas occupied by each species accounted for 24.5% in the whole Araguaia-Tocantins Basin for *B. falcatus*, 14% for *P. fasciatum*, 12% for *L. friderici* and 8.5% for *M. torquatus* (Figure 2a-d; Supplementary Material, Table S1). *Brycon falcatus* and *P. fasciatum* increased their ESN area by 12% and 16%, respectively, from the LGM to the present, while *M. torquatus* and *L. friderici* reduced their environmental suitability areas by 55% and 64%, respectively, during the same period (Supplementary Material, Table S1). All four species showed higher ESN losses in the southwestern region of the Araguaia-Tocantins Basin (Figure 2). *Pseudoplatystoma fasciatum* showed the greatest gains while *L. friderici* experienced the greatest losses during the LGM-present transition (Supplementary Material, Table S1).

In the Mortes River Basin, the predictions of environmental suitability areas indicate that currently *P. fasciatum* occupies 31% of its ESNs within the basin, *B. falcatus* 12.3%, *M. torquatus* 6.5%, and *L. friderici* 4%, predominantly in the eastern part of the basin (Supplementary Material, Table S1), in two of the municipalities where interviews were conducted, Nova Nazaré and Novo Santo Antônio (Figure 2a-d).

The species with the highest number of occurrence records used to construct the species distribution models was *L. friderici*, followed by *B. falcatus*, *P. fasciatum* and *M. torquatus* (Table 1). The three algorithms to estimate the environmental suitability areas resulted in values considered ‘very good’ for AUC and TSS (Elith 2000), indicating a predictive performance and spatial adjustments aligned

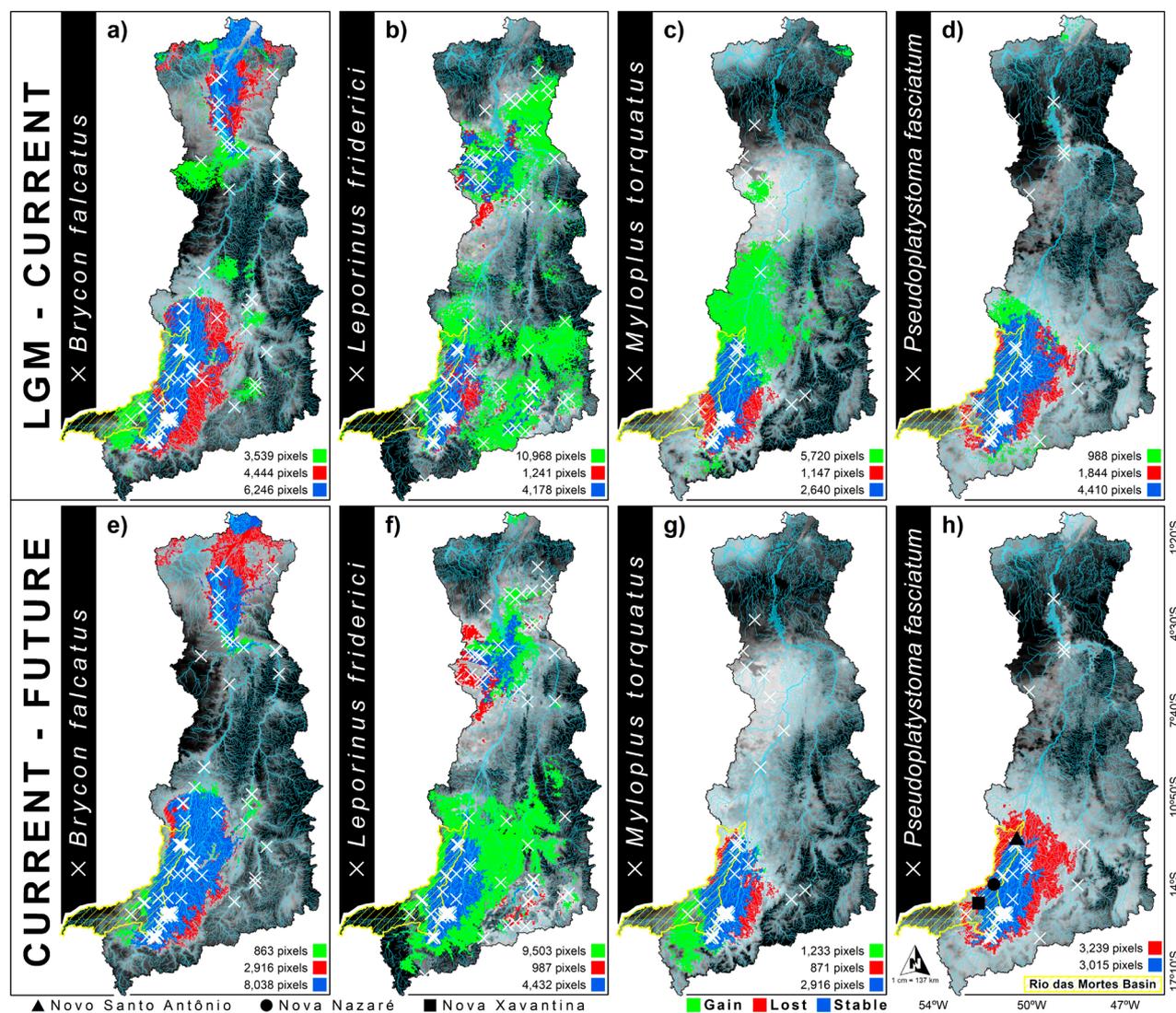


Figure 2. Spatiotemporal shift in the distribution of the environmental suitability niches (ESNs) of the four target fish species in the Araguaia-Tocantins Basin (Brazil) during the transition from the Last Glacial Maximum (~21,000 years ago) to the present (a-d) and from the present to the future projected scenario (e-h). The colors represent losses (red), gains (green) and stability (blue) of the ESNs. The yellow outline indicates the Mortes River Basin.

Table 1. Statistical performance of the algorithms and percentage contribution of the environmental variables with the greatest effects on the spatiotemporal responses of the target fish species (*Brycon falcatus*, *Leporinus friderici*, *Myloplus torquatus* and *Pseudoplatystoma fasciatum*) in the Araguaia-Tocantins Basin. N = number of occurrence records considered in the model, RF = Random Forest; GLM = general linear model; AUC = average value of area under the curve; TSS = true skill statistic; Bio2 = mean diurnal temperature range; Bio3 = isothermality; Bio13 = precipitation of wettest month; Bio14 = precipitation of driest month; Bio15 = precipitation seasonality (coefficient of variation); Bio19 precipitation of coldest quarter; Bio20 = altitude.

Species	N	Algorithm						Environmental variables (%)						
		MaxEnt		RF		GLM		Bio2	Bio3	Bio13	Bio14	Bio15	Bio19	Bio20
		AUC	TSS	AUC	TSS	AUC	TSS							
<i>B. falcatus</i>	116	0.87	0.80	0.92	0.87	0.61	0.41	15.15	3.41	9.91	0.04	2.50	18.51	50.45
<i>L. friderici</i>	977	0.91	0.84	0.90	0.88	0.68	0.58	2.75	12.25	0.00	11.41	0.73	36.04	36.79
<i>M. torquatus</i>	53	0.86	0.81	0.90	0.80	0.81	0.75	1.13	1.80	0.10	33.58	3.26	2.46	57.64
<i>P. fasciatum</i>	72	0.81	0.89	0.83	0.73	0.76	0.67	30.07	0.28	5.97	23.63	1.31	0.58	38.12

with the species' biogeography (Table 1). Altitude was the environmental variable that best explained the current spatial distribution of the four species (Table 1). *Leporinus friderici* and *B. falcatus* were also sensitive to the precipitation in the coldest quarter, *M. torquatus* to precipitation of the driest month, and *P. fasciatum* to the daily thermal amplitude and precipitation of the driest month (Table 1).

Future distribution and species conservation

The target species responded differently to the future climate projection under a pessimistic carbon emissions scenario. The transition from present to the future scenario predicted *L. friderici* to increase its ESNs, *B. falcatus* and *M. torquatus* to undergo shifts, and *P. fasciatum* to experience a loss of suitable habitat (Figure 2e-h). The environmental suitability for both *B. falcatus* and *P. fasciatum* is predicted to reduce in the Araguaia-Tocantins Basin as a whole (-19% and -52%, respectively) and in the Mortes River Basin in particular (-33.5% and -41.5%, respectively) (Figure 2e,h; Supplementary Material, Table S1). Conversely, *M. torquatus* and *L. friderici* are expected to increase their ESN area in the future, with an estimated expansion of 9.5% in the whole Araguaia-Tocantins Basin (40% in the Mortes River Basin) for the former, and up to 157% in the Araguaia-Tocantins Basin for the latter (Figure 2f,g; Supplementary Material, Table S1).

Protected areas encompassed 21% of the area of the Araguaia-Tocantins Basin (14.5% of the area of the Mortes River Basin) and can potentially conserve up to 20% of the environmental suitability area of the four target species in the Araguaia-Tocantins Basin: *B. falcatus* (20%), *P. fasciatum* (16%), *M. torquatus* (15%) and *L. friderici* (11%) (Figure 3).

DISCUSSION

Most cited species

Pseudoplatystoma fasciatum, the most frequently mentioned species in the interviews, is a large catfish of low-fat meat and no intramuscular bones, which makes it highly valuable

commercially (Crepaldi *et al.* 2006). The second most cited species, *B. falcatus* is important for sport fishing and as a food resource for riverside communities (Matos *et al.* 2020). *Myloplus torquatus* is widely distributed in South America, with highest population densities in the Amazon Basin (Nico *et al.* 2018), and is one of the most consumed species in the state of Mato Grosso (Lopes *et al.* 2017). With fewer records, *L. friderici* is sought by local fishermen as bait to catch larger fish (Ferreira *et al.* 1998). Studies on the richness, diversity, and abundance of fish in the Araguaia-Tocantins Basin (Melo *et al.* 2005; Lima *et al.* 2021) confirm the presence of the four target species in the studied area. This underscores the importance of assessing the current and future occurrence of species with economic and food interest, particularly when the social actors who rely on these species, as many indigenous and riverside communities, are made vulnerable by economic activities that impact the environment (Pinho *et al.* 2014).

Distribution and LGM to present transition

Two of the target species showed an increase in their ESNs and two decreased between the last glacial maximum and the present. It is widely accepted that at the LGM the climate of South America was drier than today, that tropical forests contracted, and rivers experienced reductions in their drainage area and discharge (Sato *et al.* 2021). For freshwater fishes, with physically restricted dispersal, past events can leave a noticeable imprint on current species and we expected, as observed in the species studied, that from the LGM to the present, some processes may have played a determining role in shaping the current population pattern (Tedesco *et al.* 2005).

Altitude, which contributed most to determine the current geographic distribution of the four species in the Mortes River Basin, directly influences the hydrodynamics and geomorphology of rivers, conditioning the presence, abundance, and richness of species, and is one of the predictors with the greatest effect on the spatial-temporal distribution patterns of ichthyofauna (Súarez and Petrere Júnior 2007). As altitude decreases, the river's surface area and depth

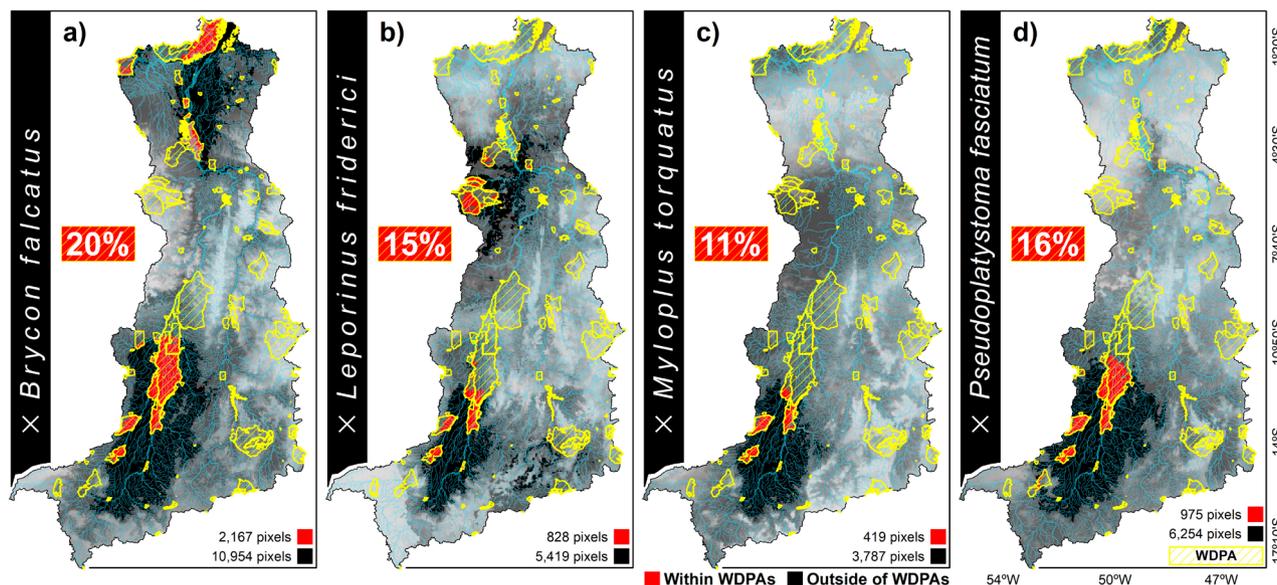


Figure 3. Continuous predictions of environmental suitability [greyscale: white (lower environmental suitability), black (higher environmental suitability)] and binary predictions of environmental suitability for niches (ESNs, black color) within Protected Areas (PAs, red filled yellow outline) and outside them (only yellow outline). The percentages represent the proportions of ESNs of the target species, overlapped with the PAs that are for the conservation of biodiversity within the Araguaia-Tocantins Basin.

increase, providing suitable habitats for larger fish species. This is the case of *P. fasciatum*, which is the largest and the most cited species by interviewees. The current distribution of *P. fasciatum* was also influenced by the temperature range. Increasing water temperature can affect the behaviour and ovarian development of this species, accelerating ontogenetic development, which can impact fish age and size classes, thereby affecting fishing activities and the local economy (Winfield *et al.* 2016).

The current concentration of the target species in the southwestern portion of the Araguaia-Tocantins Basin (northeastern Mortes River Basin) may be associated with the extensive floodplain area of the Bananal Sedimentary Plain (Martini 2006), which is subject to a seasonal climate characterized by high precipitation during the rainy season (Rosin *et al.* 2015). This variable was one of the predictors influencing the current geographic distribution of the four target species, as, for example, *M. torquatus* depends on the flood period during the rainy season to optimize feeding, reproduction, and shelter search (Beltrão and Soares 2018).

Along its 1,200 km length, the Mortes River stands out for containing extensive preserved areas and conservation units, such as the Araguaia State Park (SEPLAG 2008). However, only 20% of the environmental suitability of the target species are covered by preserved areas dedicated to conserving regional biodiversity. The lack of environmental suitability areas in the southwestern portion of the Mortes River Basin coincides with the least preserved region of the basin, that is strongly impacted by large-scale agricultural activities, such as soybean, corn and cotton, and cattle ranching (Rosin *et al.* 2015). One

suggested reason for the vulnerability of *B. falcatus* in the region is its high degree of dependence on riparian vegetation (Teresa *et al.* 2015; Matos *et al.* 2016; Borges 2018) which is largely eliminated in anthropically impacted areas.

This highlights the importance of strict adherence to the Brazilian legislation that protects the Permanent Preservation Areas (*Áreas de Preservação Permanente*) such as the vegetation on the riverbanks (Brazil 2012). Adherence to these regulations not only guarantees the maintenance of the physical and chemical quality of the water but also ensures the survival of aquatic species that rely on diverse aquatic ecosystems to complete their life cycles (Dala-Corte *et al.* 2020).

Future distribution and species conservation

In a drier and warmer future (+8.5 °C), *B. falcatus* and *P. fasciatum* are expected to exhibit reduced environmental suitability. The decrease in ESN for both species is probably related to changes in habitat structural complexity, which often result from environmental and climatic alterations such as deforestation, fires, agricultural activities, and dam construction (Matos *et al.* 2016). Furthermore, both are migratory species that rely on rainfall and flood pulses to complete their life cycle (Romagosa *et al.* 2003; Matos *et al.* 2016), and climate models project regional reductions and shifts in precipitation patterns, resulting in altered flood pulses and fluvimetry (Jiménez-Muñoz *et al.* 2016; IPCC 2023).

Brycon falcatus occurrence is typically associated with riverside vegetation, as its diet primarily consists of fruits, seeds, and flowers (Matos *et al.* 2016). Moreover, as a disperser of native tree seeds, *B. falcatus* plays a vital role in

riparian forest ecosystems (Borges 2018). Thus, in a future scenario, decreases in *B. falcatus* populations due to reduced environmental suitability could impact the dispersal of tree species, thereby affecting riparian forests and their associated biodiversity, leading to cumulative, cascading, and synergetic effects. *Pseudoplatystoma fasciatum* is a top predator that has an important function in maintaining the aquatic food webs (Crepaldi *et al.* 2006), thus, a future decrease in environmental suitability for *P. fasciatum* in the Araguaia-Tocantins Basin would not only endanger the species itself but also the regulation of population density of prey species (Silva *et al.* 2014).

The increase in environmental suitability for *M. torquatus* in the future scenario is probably linked with its generalist and adaptable diet. A niche partitioning study among fish in other Amazonian rivers involving *M. torquatus* consistently showed that its diet remains broad and generalist regardless of the flood pulse, and that *M. torquatus* primarily consumed aquatic resources, such as filamentous algae, during the dry period (Correa and Winemiller 2014). Additionally, as a species that adjusts its life cycle to rainfall and fluvionetry (Melo *et al.* 2005), the trophic plasticity of *M. torquatus* may be an important adaptation in environments subject to seasonal flooding (Röpke *et al.* 2014) and in face of new climatic and environmental conditions predicted for the future.

The predicted future expansion of environmental suitability for *L. friderici* at the scale of the Araguaia-Tocantins Basin could also be related to its opportunistic behaviour and diverse trophic strategy, which enable it to occupy different ESNs and exploit new food resources (Silva *et al.* 2014; Röpke *et al.* 2014; Beltrão and Soares 2018). Consequently, both *L. friderici* and *M. torquatus* may become increasingly important fishing resources in future climate change scenarios in the Araguaia-Tocantins Basin.

The current protected areas in the Araguaia-Tocantins Basin were estimated to cover 11% to 20% of the target species' environmental suitability areas, but only one (*B. falcatus*) surpassed the conservation target of 17% proposed in Aichi Target 11 (CBD 2020). Globally the average percentage of adequately represented climatic niche partitions per species ranged from 28.2% to 39.4% (Hanson *et al.* 2020), showing that the four target species' ESNs representation within the existing protected areas is quite below the global average. The current protected areas in the Mortes River Basin (14.5%) also fall short of the recommended in the Aichi targets and in the Brazilian National Biodiversity Targets, both established at 17% (CBD 2020; MMA 2023b). To achieve the target of protection, an additional coverage of ~25,000 hectares will be required.

The complexity of protecting inland waters suggests that it could require greater areas than those needed to achieve the protection for terrestrial environments (Abell *et al.* 2007). Currently protected areas of freshwater ecosystems are of limited effectiveness in safeguarding freshwater biodiversity,

therefore establishing new protected areas are an integral part of conservation strategy proposals (Farias *et al.* 2019; Lima *et al.* 2021), considering that Brazil has committed to achieving the goals set in the Aichi Biodiversity Targets (CBD 2020). The Araguaia sedimentary floodplain that contains the *Ilha do Bananal* RAMSAR site (MMA 2023a) is strategic for conserving freshwater and riparian species that inhabit the transition between the Cerrado and Amazonia biomes (Latrubesse *et al.* 2019). Yet, this one conservation unit is likely insufficient to ensure the effective protection of this important, vast and highly impacted wetland area. Therefore, we propose the creation of new conservation units and the designation of new RAMSAR sites in the Araguaia-Tocantins Basin which, in addition to ensuring the conservation of biodiversity (Lima *et al.* 2021), could contribute to the conservation of important fish species used by riverside communities.

CONCLUSIONS

Our analysis showed that the current geographic distribution of four species of importance for commercial and subsistence fishing in the Mortes River Basin was predominantly influenced by different climatic variables. *Pseudoplatystoma fasciatum* and *B. falcatus* showed relative spatial fidelity from the Last Glacial Maximum to the present, but are projected to have their environmental suitability area much reduced in a future climate of +8.5 °C. Conversely, *M. torquatus* and *L. friderici* were estimated to have shrunk their distribution area in over 50% since the LGM, but are expected to have their environmental suitability increased in the Araguaia-Tocantins Basin in a future warmer climate, especially *L. friderici*. The current protected areas in the Araguaia-Tocantins Basin provide insufficient cover to the environmental suitability area of the target species, indicating the need for the creation of new conservation units that consider the environmental suitability areas of species and their projected response to future climate scenarios. This information is especially important for fishing resources, in order to assure their future conservation for indigenous and riverside communities along the southern Amazonian border. We expect that the obtained predictions can guide future management, mitigation, and conservation plans for these species.

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SUPPLEMENTARY MATERIAL

Mancini *et al.* Conservation status and spatiotemporal distribution of fish with socioeconomic importance in the Amazonia-Cerrado transition zone

Table S1. Basin and estimated occurrence area (km²) of the four target fish species in the whole Araguaia-Tocantins River Basin (Brazil) and in the Mortes River Sub-basin in the Last Glacial Maximum (LGM), present and future scenarios simulating current environmental variables in SSP5-8.5 (WorlClim 2.0) and using the Model for Interdisciplinary Research on Climate (MIROC6) for climate predictions and future projections.

Mortes River Basin (total area = 61,276 km ²)				
Period	<i>Brycon falcatus</i>	<i>Myloplus torquatus</i>	<i>Leporinus friderici</i>	<i>Pseudoplatystoma fasciatum</i>
Present	7,561	3,998	2,382	18,995
Future	5,033	5,593	2,216	11,124
Araguaia-Tocantins Basin (total area = 774,821 km ²)				
LGM	169,877	145,137	262,949	93,714
Present	190,172	65,746	94,079	108,575
Future	154,530	72,030	241,925	52,343

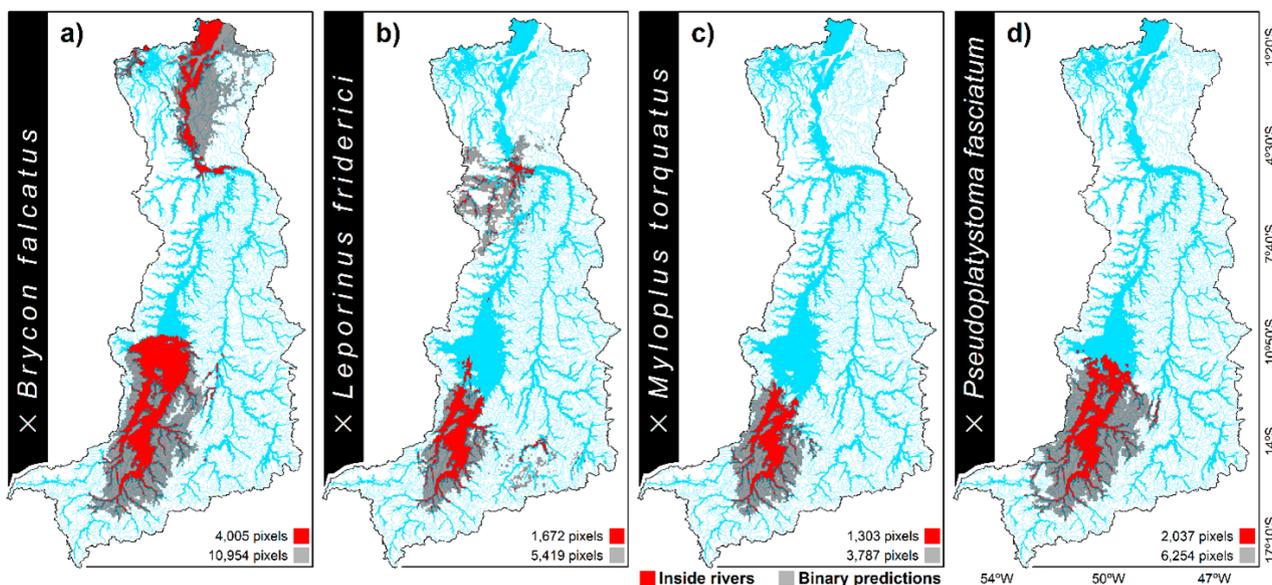


Figure S1. Binary predictions of environmental suitability niches (ESNs, in gray) of the four target fish species (red) in the hydrological network (blue) of the Araguaia-Tocantins Basin (black outline).