An Acad Bras Cienc (2024) 96(3): e20231343 DOI 10.1590/0001-3765202420231343
Anais da Academia Brasileira de Ciências | *Annals of the Brazilian Academy of Sciences*
Printed ISSN 0001-3765 I Online ISSN 1678-2690
www.scielo.br/aabc | www.fb.com/aabcjournal

ECOSYSTEMS

Arapaima gigas stocks have declined drastically in the lower Tocantins River in the Amazon Microregion

DARALYNS B. MACEDO, JEANDERSON S. VIANA, HENDRYA JULIANNY P. COELHO, CAIO VITOR C. COSTA, DÁRCIA GABRIELA B. DA COSTA, ÁDRIA D. DOS SANTOS, REGIANNE M.S. CORREA, ROMMEL THIAGO J. RAMOS & MARÍLIA DANYELLE N. RODRIGUES

Abstract: *Arapaima gigas*, an emblematic species of the Amazon region and a longstanding primary fishing resource, currently holds a "Data Deficient" status on the International Union for Conservation of Nature Red List, and is listed as an endangered species in Brazil. The Tocantins River is the most extensively modified large tributary of the Amazon Basin, and thus can affect the dynamics of ichthyofaunal populations. Over a period of 1 year, representatives of the fishing communities and fishermen from 25 fishing communities from four municipalities in the lower Tocantins River region were interviewed, and the obtained information was evaluated based on the literature to survey the population abundance status of *A. gigas* in the region and its impact on local communities. Among the fishermen interviewed, only one reported still encountering and fishing *A. gigas* on Jaracuera Island. The disappearance of *A. gigas* in the region are viewed as having economically disastrous consequences for the residents. Additionally, other endemic fish species are no longer observed in this locality either. If fishery management officials do not work together with local communities, *A. gigas* could disappear from the northern region of Brazil, where information on the dynamics of *A. gigas* fishing is lacking.

Key words: Amazon Region, Fisheries, Hydroelectric Power Plan, Ichthyodiversity, Pirarucu, Traditional Communities.

INTRODUCTION

The Tocantins River Basin is one of the largest bodies of water in the eastern Amazon. With a total area of 764,996 km², this region is larger than countries such as France and Ecuador (de Jesus et al. 2020), and is the only river valley in the Brazilian Amazon that encompasses more than three states and different biomes, including the Cerrado, Plateau, and Amazon Forest (Oliveira-Filho & Ratterf 1995). Owing to its evolutionary history among the Amazonian tributaries, the lower Tocantins River harbors diverse ichthyofauna, which are closely associated with Amazonian species, and has high fish species richness (Dagosta & Pinna 2019).

Arapaima gigas (Schinz 1822), known as "Pirarucu" in Brazil and "Paiche" in Peru and Bolivia, is an emblematic fish of the Amazon region (Miranda-Chumacero et al. 2012). Once considered the most important fishing resource in the Brazilian Amazon (Castello et al. 2015), this species plays a crucial role in supporting the livelihoods of traditional communities in the region with regards to ethnopharmacology (Alves & Rosa 2007) and food (Prestes-Carneiro

et al. 2016). Furthermore, *Arapaima* spp. are considered premium fish from which products with a high potential for competition in the fishing market, such as frozen or salted fillets and loins, can be obtained (Mesquita et al. 2022). This provides both employment and a source of income for local fishermen, highlighting the importance of the *A. gigas* chain.

At the end of the 20th century, *A. gigas* was listed in Appendix II of the Convention on International Trade in Endangered Species of Fauna and Flora because of commercial fishing pressure in the Amazon River (Castello & Stewart 2010). This has led to efforts by riverside communities to implement local measures aimed at rational utilization of *A. gigas* fisheries, which received legal recognition from the Brazilian government in the late 1990s (Francisco et al. 2015). Currently, *A. gigas* is listed in the "Almost Threatened" category on the Brazilian list of endangered species (MMA 2018); however, in 2016, *A. gigas* was not listed due to insufficient distribution and population abundance data (Castello et al. 2015). Internationally, this species is categorized as "Data Deficient" on the Red List of the International Union for Conservation of Nature (World Conservation Monitoring Centre 1996), highlighting the need for sufficient information to assess the risk of extinction of the species.

Human activities are the main contributor to the global decline in biodiversity. Urban expansion and agriculture have resulted in the destruction, fragmentation, and loss of habitats for several animal and plant species that cannot adapt to the stresses imposed by human-altered environments (Hunter 2007). The decline in biodiversity poses a major risk to the functioning of ecosystems and their capacity to provide society with essential goods and services. Simplified ecosystems only yield short-term gains, but their costs are incurred by future generations (Cardinale et al. 2012). The inauguration of one of the largest hydroelectric projects worldwide on the Tocantins River has been predicted to have disruptive effects on the local socioeconomy, directly affecting subsistence activities such as fishing (Barrow 1987). Currently, the Tocantins River is the most extensively modified large tributary in the Amazon Basin (Davidson et al. 2012).

Variations in the dynamics of ichthyofaunal populations can be easily identified by traditional communities engaged in subsistence fishing activities. The causes of these variations are identified over the long term because of ethnoenvironmental knowledge that has been developed and passed down over generations (Fainguelernt 2020). To improve our understanding of the future effects of environmental changes in the lower Tocantins River on the local bioeconomy supported by *A. gigas* fishing, we evaluated the environmental perceptions of fishing communities in the lower Tocantins River in terms of the population abundance of *A. gigas* and its relationship with human activity.

MATERIALS AND METHODS

Study area

In this study, fishing communities belonging to the municipalities of Baião, Cametá, Igarapé-Miri, and Mocajuba in the State of Pará, northern Brazil, were interviewed (Figure 1). The study region is located on the banks of the lower Tocantins River.

The region has an average annual temperature of 26 °C, a humid tropical megathermal climate with an annual rainfall of approximately 2,000 mm, and a well-defined climatic period with the highest flows from December to May and lowest from August to November (IDESP 2014).

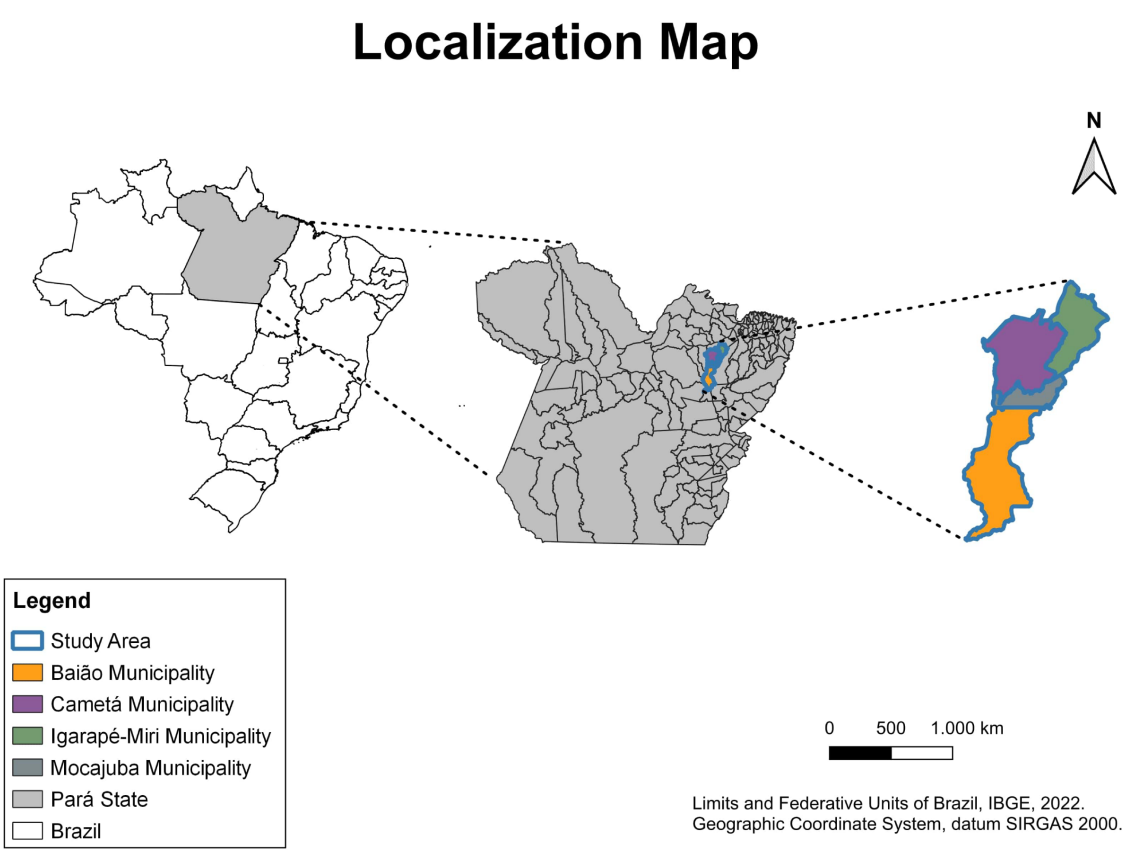

Figure 1. Map of the study area in Amazon municipalities in the State Pará, Brazil.

The Baião, Cametá, Igarapé-Miri, and Mocajuba municipalities have areas of 3,202,399, 3,081,367, 1,996,790, and 871,171 km^2 and have approximately 49,454, 140,814, 63,367, and 31,917 inhabitants, respectively (IBGE 2021).

Data collection

From December 2017 to December 2018, 25 fishermen from 25 fishing communities in the lower Tocantins River region were interviewed (Table I). Interviews were structured based on personal data, population censuses of *A. gigas* in the region, fishing activities, and related information. Open- and closed-ended questions were also used. Each interview was based on the indications of the representatives of the fishing communities and fishermen according to the non-probabilistic snowball sampling technique (Vinuto 2014).

Open information cited by fishers, such as the species of fish caught and the relationships identified between changes in fish population dynamics and human interventions in the environment, were recorded in a trip report. Fish catalogs from Baixo Tocantins were used (Santos et al. 2004).

Assessment of published and unpublished information

We conducted a survey of the information published in scientific articles on population studies of *A. gigas*, fishing management plans, and conservation of the species in Brazil and globally. The information obtained from the questionnaires was compared to identify new information and predict the population abundance status of *A. gigas* in the lower Tocantins River region and its impact on the local community.

Table I. Number of respondents per fishing community and municipality

Municipality	Fishing community	Number of respondents
Baião	Limão	6
	Vila Iteguara	
	Joana Peres	
	Boa vista	
	Itaperuçu	
	Vila Bom Sucesso	
Cametá	Ilha de Itamduba	9
	Jurmate	
	Ilha Marinteua	
	Ilha Jakacuera-Curuçambaba	
	Ilha Murucu Carmo	
	Ilha Jaracuera	
	Cuxipiari Carmo	
	Itaúna Baixo	
	Santa Maria do Maracu	
Igarapé-Miri	Joarimbu	6
	Ilha da Santana da Conceição	
	Muritipucu	
	Panacuera	
	Pindobal Grande	
Mocajuba	Ilha do Tauaré	4
	Ilha da Santana	

RESULTS

Fishing activity and social value

The interviewed fishermen were between 33 and 69 years of age and had been fishing since childhood or their youth. Fishing was identified as the main activity of those interviewed, followed by agriculture with the planting of cassava and sugarcane. The number of family members interviewed who depended on fishing reached 55 for a single fisherman whose brothers, children, and grandchildren were involved in additional activities and trade in the fishing chain in the municipality of Cametá.

For people who depended solely on fishing for subsistence, the lowest monthly income per family reached 200 reais, and the highest, with government aid, was approximately 1,320 reais. All the local communities stated that they depended on fishing for subsistence, with some fishing only for their own consumption or to sell and buy other sources of protein such as beef and poultry. Statements regarding fishing being essential for family sustenance were common.

Most fishermen reported an increase in the price and demand for fish, but claimed that the quantity caught has decreased drastically in recent years, which has harmed their families' livelihoods.

Perception of population abundance of *A. gigas*

Among all the fishermen interviewed from the four municipalities studied, only one reported still finding and fishing *A. gigas* in Ilha Jaracuera, Cametá municipality, between March and October. Individuals reported fishing for their own consumption. Fishermen from the community located in the Joana Peres extractive reserve (resex ipaú-anilzinho), Baião municipality, reported a decline in *A. gigas* populations over the last 20 years in which they have been practicing fishing. During this period, they observed changes in the way the species was fished, such as the replacement of harpoons with nets, indicating that more fish were captured. The disappearance of *A. gigas* has had economically disastrous consequences for the residents, with one 68-year-old fisherman from Cametá municipality stating "today *A. gigas* is needed, it costs 20.00 reais per kilo," with the value referring to the market for the final consumer in the region.

In addition to the disappearance of *A. gigas* stocks and populations in the Lower Rio Tocantins region, fishermen have noted drastic population declines in other species such as *Piaractus mesopotamicus*, *Piaractus brachypomus*, *Semaprochilodous taeniurus*, *Pseudoplatystoma corruscans*, *Brachyplatystoma filamentosum*, *Prochilodus nigricans*, and *Brycon amazonicus*.

Perception of anthropogenic activities related to the decrease in *A. gigas* stocks

The fishermen suggested several causes for the change in the population dynamics of *A. gigas* (Table II), with the main reason being environmental changes caused by the construction of the Tucuruí hydroelectric plant, and secondary reasons being overfishing and pollution in the Tocantins River and its tributaries. Despite this, there have been no reports of dead fish being found, only their disappearance. According to the ethnoenvironmental knowledge offered by the fishermen, the human activities mentioned have a direct effect on the successful adaptation of *A. gigas* to the altered environment, which suggests that the pressure induced by overfishing of the species is greater than its resilience to environmental stresses.

Inspection over local fishing was categorized at the national, municipal, and local levels, which fishermen defined as efficient only at the local level through the so-called "fishing agreements" that many fishermen claimed to be part of. They also highlighted the low frequency of inspection and control overfishing by government bodies: "I would be happier if the competent bodies controlled fishing", "People say there is supervision, but I have never seen it", "There is, but it is little...once a year". The quantities caught and demanded, and the price paid for fish are the types of information that communities state to have no public institutional monitoring.

DISCUSSION

Disappearance of *A. gigas*

The absence of *A. gigas* in the lower Tocantins River and its tributaries was the predominant perception of fishermen from

Table II. Ethnoenvironmental knowledge of fishermen associated with the disappearance of *A. gigas* in the municipalities of Igarapé-Miri, Cametá, Mocajuba and Baião in the North of Brazil.

Municipality	Ethnoenvironmental knowledge
Igarapé-Miri	*"Catch fish near natural nursery"*
Mocajuba	*"Lots of people fishing, this can cause fishing problems"*
Igarapé-Miri	*"The dam caused the fish to be drowned"*
Baião	*"With the hydroelectric plant, there is not enough water at the right time for the fish to spawn"*
Baião	*"It is planned to excavate the Tocantins River, Pedral do Lourenço project...no benefit for fishermen...it will scare the fish away to other areas"*
Cametá	*"Prohibited equipment and use of poison (ant barrage)"*
Cametá	*"The dam dried up the river and the fish disappeared"*
Cametá	*"Lots of people fishing in the same place"*

all local communities visited. Furthermore, a reduction in the stocks of other fish species was observed. According to them, the most plausible justification for the situation was the construction of the Tucuruí Hydroelectric Plant in the region.

Hydroelectric plants can affect the ichthyofauna of a watercourse, resulting in changes in diet (Agostinho et al. 2008), size reduction (Santos et al. 2018), occurrence of new species (Orsi & Britton 2014), and decreased fishing yield (Carvalho et al. 2021). *A. gigas* is particularly susceptible to environmental changes due to its reproductive behavior, which is characterized by specific requirements and is directly stimulated by variations in water levels (Núñez et al. 2011).

Arapaima gigas is a socially monogamous species that builds nests in shallow, slow-flowing waters, and spawns partially annually or every 2 years (Galvão et al. 2012, Marková et al. 2020). Individuals of this species reach sexual maturity at 5 years of age, when they reach a size and weight of >160 cm and >40 kg, respectively (Imbiriba 2001). Although this species is considered sedentary, researchers have reported that *A. gigas* migrates laterally between rivers and floodplain habitats during periods of high-water levels and flooding to spawn, moving to increasingly higher habitats in flooded forests and returning as water levels decrease (Monteiro et al. 2010, Castello 2008). Fish such as *A. gigas*, which depend on varying water levels for reproduction, are more vulnerable to the environmental effects of hydroelectric dams (Arantes et al. 2019).

After damming, fish stocks will respond differently to habitat modifications depending on the biology and functional characteristics of the species (Arantes et al. 2019). Population changes and their magnitudes can be predicted in investigations that focus on the specific characteristics of a target species (Balzannikov & Vyshkin 2011). Ethnoichthyological knowledge and the environmental perceptions of fishermen provide critical information to government institutions for defining the best public policy strategies to mitigate anthropogenic effects on *A. gigas* populations in the region. Recommendations for solutions require arguments based on local environmental perceptions and scientific investigations (Mesquita et al. 2022).

Amazon conservation lessons

A misconception of the Amazon region stemming from its history of Portuguese colonization is that it has an overabundance of natural resources, characterized as inexhaustible regardless of human demand (Goulding et al. 2000). This has led to substantial exploitation of the native fauna and severe population declines of several fish species, such as *A. gigas* (He et al. 2017).

In regions where *A. gigas* has been extirpated, three characteristics have hampered sustainable fishing of the species: the absence of data to identify population decline, overfishing or illegal fishing due to inefficient enforcement of fishing regulations, and geographic heterogeneity that compounds inter-community differences in fishing practices and ecological conditions (Castello et al. 2015). These characteristics are prevalent in tropical countries and lead to unnoticed fishing-induced extinctions (Pauly et al. 1989). The data obtained from the environmental perceptions of fishermen indicate a state of concern regarding the population decline of *A. gigas* in the lower Tocantins River, as the three characteristics of susceptibility to extinction of the species are strongly highlighted by fishermen, among which the lack of data is related to limited inspection and monitoring.

In 1996, the same year that *A. gigas* fishing was banned in the Amazon River (IBAMA 1996), the Mamirauá Ecological Station (MES) was declared a reserve for sustainable development, with the local community aiding in biodiversity conservation through the use of natural resources (Castello et al. 2011). The MES conducts participatory management based on catch quotas per fisherman, salted fillet processing, planned sales, and stock control using a counting method based on the number of times the animal surfaces to breathe (Rosa et al. 2020). In 8 years, the *A. gigas* population increased from 2,200 to 20,650 individuals and collection quotas increased from 120 to 1,249 individuals, resulting in greater monetary returns for fishermen and a growing interest in the activity (Castello et al. 2009). In protected areas with community management, the average annual income from *A. gigas* fishing can reach US$10,601 per community and US$1,046.6 per household, as analyzed in the Juruá River of the Western Brazilian Amazon, in which efficient fisheries management improved the socioeconomic well-being of the local population (Campos-Silva & Peres 2016).

The studied area has a high potential for fishing, as it comprises a large number of communities whose main activity is fishing (Hallwass et al. 2011). However, the low economic returns and lack of young people interested in fishing present major obstacles to economic development and the maintenance of traditional practices in the region based on *A. gigas* fishing (Galvão et al. 2012). In the middle Tocantins River, a region close to the study area, damming caused considerable damage to the working conditions of local fishermen, leading many fishermen to abandon their profession (Santos & Pelicice 2023). Consequently, protected areas with community management (Figure 2), such as the Mamirauá Sustainable Development Reserve, can not only aid in the recovery of *A. gigas* fishing stocks but also prevent rural

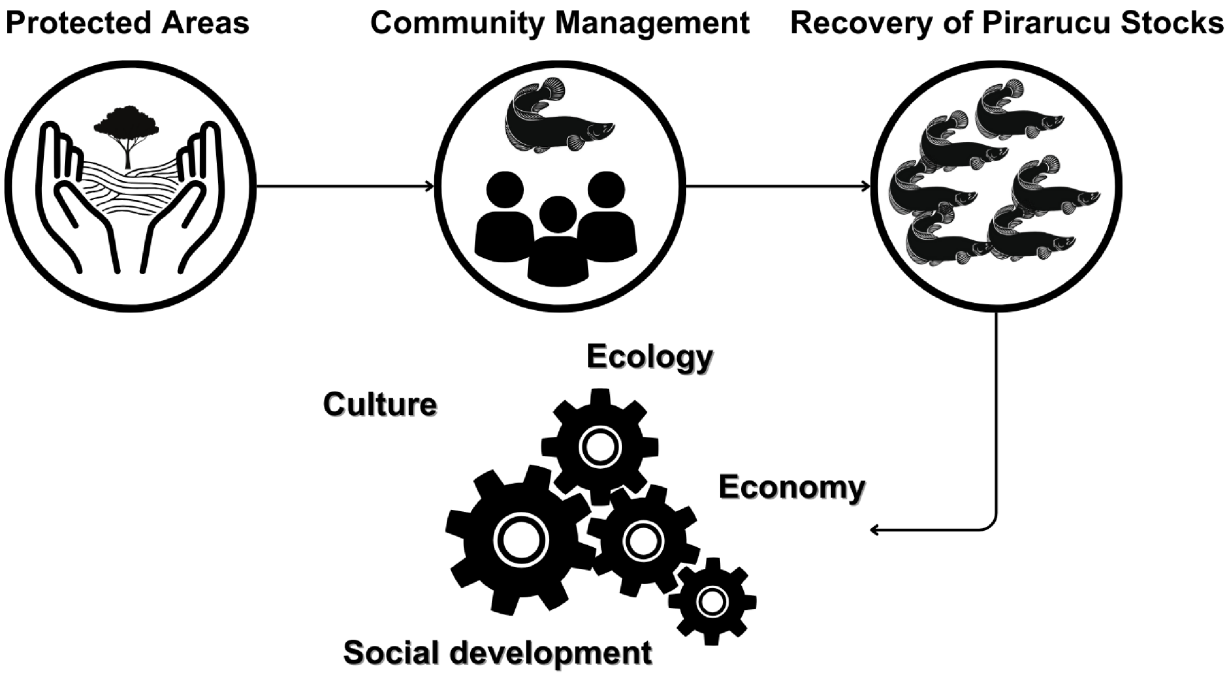

Figure 2. Flowchart of economic, social, and environmental sustainability based on *Arapaima gigas* conservation in native areas.

exodus and the gradual reduction of artisanal fishing in the State of Pará (Fuzetti & Corrêa 2018).

Arapaima and flow of ecosystem services

Ecosystem services (ES) sensu stricto are the benefits that people obtain from ecosystems and are coproduced by their interaction with society, and are essential for human survival (Balvanera et al. 2017). ES are divided into four categories: supply services (products obtained for food, subsistence, and commerce), regulation services (services that balance the natural conditions of the environment), cultural services (non-material benefits), and support services (basis for the performance of other services) (Lamarque et al. 2011). The flow of ecosystem services (ESF) represents the quantity of a service used or delivered through transmission channels, regardless of the origin of the service (Bagstad et al. 2020). The ESF is derived from the spatial relationship between the supply and demand of an ES concentrated in its flow from a supply area to a benefiting area (Bagstad et al. 2014). Financing is crucial for the success of species conservation; therefore, the benefits of ES, monitoring population development, and capturing individuals are essential (Plantinga et al. 2023).

Fishing plays an important role in providing goods and services from an ecosystem such as nutrient cycling, biological regulation, social relationships, knowledge systems, and cultural identity (Bladon et al. 2016, Gelcich et al. 2019). In addition to fishing for personal consumption, the Amazonian *A. gigas* fishing chain is directly related to cultural and recreational ecosystem services, offering a tourist opportunity to savor regional dishes prepared with exquisite fish meat and learn about Amazonian mythology surrounding the emergence of *A. gigas*, which describes it as an indigenous warrior who became a fish (Carvalho et al. 2018). This study may contribute to the exploration of ESs involving *A. gigas* as a basis for multifunctional livelihoods in northern Brazil and other areas of *A. gigas* occurrence in the world.

CONCLUSIONS

A. gigas stocks have declined drastically in the lower Tocantins River after the construction of the Tucuruí Hydroelectric Plant, which fishermen pointed out as the main factor for the decline in the species' population. The lack of adequate fishing management in northern Brazil directly affects the economic well-being of communities that are dependent on fishing, which could lead to the disappearance of traditional artisanal fishing in the area and consequent rural exodus. The urgency of solutions based on environmental protection and community management may return to the population recovery of *A. gigas* and social development in the State of Pará.

Acknowledgments

To the fishermen of the lower Tocantins River for their reception and willingness to answer the questionnaires. To the Integrated Postgraduate Program in Animal Science in the Tropics from Universidade Federal Rural da Amazônia for the financial support for the translation of the scientific article.

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How to cite

MACEDO DB, VIANA JS, COELHO HJP, COSTA CVC, COSTA DGB, SANTOS ÁD, CORREA RMS, RAMOS RTJ & RODRIGUES MDN. 2024. *Arapaima gigas* stocks have declined drastically in the lower Tocantins River in the Amazon Microregion. An Acad Bras Cienc 96: e20231343. DOI 10.1590/0001-3765202420231343.

Manuscript received on December 18, 2023;
accepted for publication on April 7, 2024

DARALYNS B. MACEDO[1,3]
https://orcid.org/0000-0002-0186-8149

JEANDERSON S. VIANA[2]
https://orcid.org/0000-0001-8880-1053

HENDRYA JULIANNY P. COELHO[1]
https://orcid.org/0000-0001-6793-6792

CAIO VITOR C. COSTA[1]
https://orcid.org/0000-0003-3572-4159

DÁRCIA GABRIELA B. DA COSTA[1]
https://orcid.org/0000-0001-9964-5041

ÁDRIA D. DOS SANTOS[1]
https://orcid.org/0009-0003-1194-8809

REGIANNE M.S. CORREA[1]
https://orcid.org/0000-0002-9837-4304

ROMMEL THIAGO J. RAMOS[3]
https://orcid.org/0000-0002-8032-1474

MARÍLIA DANYELLE N. RODRIGUES[1]
https://orcid.org/0000-0003-0008-0912

[1]Federal Rural University of the Amazon, Applied Genetics Laboratory, Socio-environmental and Water Resources Institute, 2501 Tancredo Neves Avenue, Terra Firme, 66077-830 Belém, PA, Brazil

[2]Federal Rural University of the Amazon, Tropical Aquaculture Laboratory, Socio-environmental and Water Resources Institute, 2501 Tancredo Neves Avenue, Terra Firme, 66077-830 Belém, PA, Brazil

[3]Federal University of Pará, Institute of Biological Sciences, Augusto Corrêa Street, nº 01, Guamá, 66075-110 Belém, PA, Brazil

Correspondence to: **Marília Danyelle Nunes Rodrigues**
E-mail: nunes.mdnunes@gmail.com

Author contributions

Daralyns Borges Macedo: original draft writing, review, and editing. *Hendrya Julianny Pereira Coelho:* analysis and interpretation of data. *Caio Vitor Conceição Costa:* analysis and interpretation of data. *Dárcia Gabriela Borcem da Costa:* analysis and interpretation of data. *Ádria Diva dos Santos:* analysis and interpretation of data. *Regianne Maciel dos Santos Correa:* analysis and interpretation of data. *Rommel Thiago Jucá Ramos:* a critical review for important intellectual content. *Marília Danyelle Nunes Rodrigues:* acquisition of data, critical review for important intellectual content, review and editing.