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Research Article

Status of *Arapaima* spp. in Brazil: threatened in its places of origin, a rapidly spreading invader elsewhere

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Abstract

The introduction of non-native fish poses a major threat to aquatic fauna in freshwater ecosystems around the world, often as a consequence of increased predation pressure, which results in adverse environmental and socioeconomic effects. In this study, we present a survey of publicly available information on the occurrence of pirarucu (*Arapaima* spp.) throughout Brazil, with an emphasis on the status of native and non-native populations, and discuss the implications for the conservation of aquatic biodiversity and the urgent need for strict control and monitoring of pirarucu breeding programs, especially in regions where it is non-native. We believe that researchers and public policy makers/managers should collaborate in managing introductions of non-native fish, and develop regulations, scientific research, risk assessments, and environmental education with this end in mind.

Key words: Amazon basin, exotic species, fisheries management, fish farming, pirarucu

Introduction

Species invasions constitute a major threat to biodiversity and ecosystem functioning worldwide (CBD 2008; Clavero and Gárcia-Berthou 2005), particularly in regions such as Brazil, the country with the greatest freshwater biodiversity (Vitule et al. 2009, 2019). Despite Brazil having a large and complex network of freshwater ecosystems and ecoregions, it has few protections to prevent and control species invasions, raising questions about the long-term prospects for its incredible biodiversity (Patoka et al. 2018). In this context, it should be noted that recent studies have

highlighted the importance of monitoring and quantifying intracountry introductions (Vitule et al. 2019).

One of Brazil's most emblematic fish species is the pirarucu, with four species in the genus *Arapaima*, and the world's largest freshwater fish with scales, growing to three meters in length and 200 kgs in weight (Castello 2004; Alcántara-Bocanegra et al. 2006; Carvajal-Vallejos et al. 2011; Ferreira 2013). The native distribution of pirarucu is thought to include the Amazon and the Araguaia-Tocantins basins (Imbiriba et al. 1993; Goulding et al. 2003; Farias et al. 2019). A record of heavy exploitation pressure beginning in the 18th century has extirpated many populations of pirarucu (Castello et al. 2015), leading *Arapaima gigas* unique species until 2013, to be included in many Brazilian red lists, and in the IUCN Red List of Endangered Species and Appendix II of the Convention of International Trade of Endangered Species (e.g. World Conservation Monitoring Centre 1996, see reference in Appendix 1; Kirsten et al. 2012).

Attention to pirarucu has grown in recent years for two main reasons. The first is its cultural and economic value among the riverine human communities (e.g. Olden et al. 2004) of the Amazon basin, which led to the development of new forms of management. Hundreds of riverine communities are now sustainably managing and, hence, conserving pirarucu in the Amazon via community-based management schemes that involve local fisheries, NGOs, and government agencies (Castello et al. 2009; Campos-Silva et al. 2019). The second is a rapid increase in the use of *Arapaima* for fish farming. Fish farming in Brazil has grown rapidly as an economic activity for which pirarucu possesses many desirable characteristics, including fast somatic growth (i.e. 80 cm of length in one year; Arantes et al. 2010), the ability to tolerate low water quality conditions (Imbiriba 2001), and a high market value (Pereira-Filho et al. 2003). As a result, there are many aquaculture initiatives seeking to develop the technology to breed pirarucu in captivity (Cavero et al. 2003, 2004). Another important issue is that, because of its beauty and size, pirarucu has been widely used in all states of Brazil (except the state of Rio Grande do Sul) as a kind of ornamental fish keeping. Even more, informal sales, such as the non-regulated trade on popular social media, of large-bodied non-native ornamental fishes (known as "tankbusters") are increasing among Brazilian hobbyists (Magalhães et al. 2017). The situation is exacerbated by the availability of pirarucu fry for sale on commercial websites (e.g. https://www.mfrural.com.br/detalhe/223960/alevinos), which has allowed many ornamental fish enthusiasts to acquire them with little governmental oversight; *Arapaima* sales on the web was pointed out as a high-risk concern in recent studies attempting to quantify the risk associated with the sale of propagules and fish invasiveness (e.g. Magalhães et al. 2017).

Today, while conservation schemes for pirarucu in their native range are booming, there is evidence that *Arapaima* is being widely relocated and

introduced in non-native ecosystems, sometimes by accident, sometimes intentionally. In some cases, these introductions have led to the long-term establishment of pirarucu populations outside of their native range. For example, in Bolivia, introduced populations of pirarucu have led to major negative impacts on traditional fishing activities, economic losses for local peoples, and the decline in the diversity of stocks of native fish species (Carvajal-Vallejos et al. 2011; Miranda-Chumacero et al. 2012; Carvalho et al. 2015; Doria et al. 2020). This problem has also been reported in the state of Rondônia in Brazil, where approximately 1,000 pirarucu fry were introduced into the rivers of the region in 1977, in a joint action between the Secretariat of Agriculture and the Superintendence of Fisheries Development (A Tribuna 1977, see reference in Appendix 1). In addition, with the expansion of pirarucu farms in much of Brazil, and the lack of government inspections to monitor the measures used to control the species in the breeding systems, some individuals have accidentally escaped via drainage systems (small young fish), due to flooding of fish farms during large floods (Agostinho and Julio 1996), or by leaks in the walls of tanks (Orsi and Agostinho 1999). Recently, the scenario of increasing introductions of pirarucu outside their native range was exacerbated by the easing of environmental legislation for the rearing of non-native species in captivity in Brazil (Rosa et al. 2020).

The current situation, therefore, includes a series of factors that, on the one hand, promote the introduction of pirarucu in different regions of Brazil (Carvalho et al. 2015; Casimiro et al. 2018; Doria et al. 2020; Pereira et al. 2021). On the other hand, however, mechanisms to prevent or control the possible adverse effects of associated invasions of pirarucu are largely lacking in Brazil, creating a possible threat to its freshwater ecosystems (Latini and Petrere Jr. 2004; Pimentel et al. 2005; Pelicice and Agostinho 2008; Casimiro et al. 2010; Leão et al. 2011; Moraes et al. 2017). Avoiding what could become a serious situation requires information on the extent to which pirarucu has been introduced across Brazil. Such information, however, does not exist in an easily accessible form, impeding necessary policy action.

The present study aims to: (1) exhibit the geographical distribution of pirarucu throughout Brazilian freshwater ecosystems; and (2) identify the mechanisms that drive its introductions. This information will be useful in the development of strategies for managing pirarucu in a safer way, one that aims at the economic sustainability of fish farming while ensuring the maintenance of diversity and stocks of native fish despite this potential invader.

Materials and methods

For the acquisition of the data, we conducted an intensive historical review of the literature related to the genus *Arapaima* published during the past forty years. The literature included scientific research papers, technical

namely Google Scholar, Scientific Electronic Library Online (SciELO), and the Web of Science, and a combination of the following keywords: *Arapaima*, pirarucu, Amazon basin, fish stocks and fish farming, and allowed the inclusion of publications over the period of 1981 to 2021.

The searches in the databases yielded 93 citations. These formed the corpus of the study and allowed the creation of a database with georeferencing information based on the locations cited in the reports. From these we created a thematic map using Quantum GIS 3.10.13 (Development Team – Open Source Geospatial Foundation Project 2021) showing the occurrence of *Arapaima* spp. throughout the territory of Brazil. Occurrence and mapping records were categorized into three distinct groups related to the stage of biological invasion (Blackburn et al. 2011): i) native – in the area of natural distribution; ii) pisciculture – outside the natural range, but still contained in captivity and iii) invasive – common, reproducing, and dispersing on its own in a natural environment outside of its native range.

Results and discussion

Assessment of the geographical distribution and status of pirarucu in Brazil

In the present study, we verified 319 occurrence records of *Arapaima* spp. cataloged throughout the territory of Brazil (Figure 1, Supplementary material Table S1). *Arapaima* spp. is considered to be an introduced species in 230 locations (72%), a native in the rest (28%).

Most of the occurrence reports in areas where the species is considered to be native are in the northern region of Brazil (80 of 89 reports – 90%); the remaining nine reports (10%) are from the mid-western region, in the state of Mato Grosso. Among the locations where it is considered to be introduced, 80% correspond to fish farms, where pirarucu is farmed using different systems (extensive, semi-intensive, intensive and super intensive) and different farming modalities (monoculture and polyculture) (Agostinho and Júlio Jr. 1996; Richardson et al. 2000). It is important to bear in mind that for a fish to become invasive it must first become established and then spread in the enviroment, since a non-native introduced species may or may not become an invasive (e.g. Casimiro et al. 2010).

In the present study, it was found that 58.3% of the farming of pirarucu in Brazil takes place outside its natural occurrence area (27.7% in the northeast, 26.5% in the southeast, 2.6% in the south and 1.7% in the Federal District), while 41.7% takes place in regions where it is considered to be native (25.7% in the north and 16.0% in the mid-west). This suggests that pirarucu is established and distributed throughout the national territory as a result of policies promoting intensive aquacultural production accompanied by the potential for escapes. In addition, it is important to highlight that the limited access to information and the lack of environmental licensing (and, therefore, registration) of aquaculture enterprises suggests

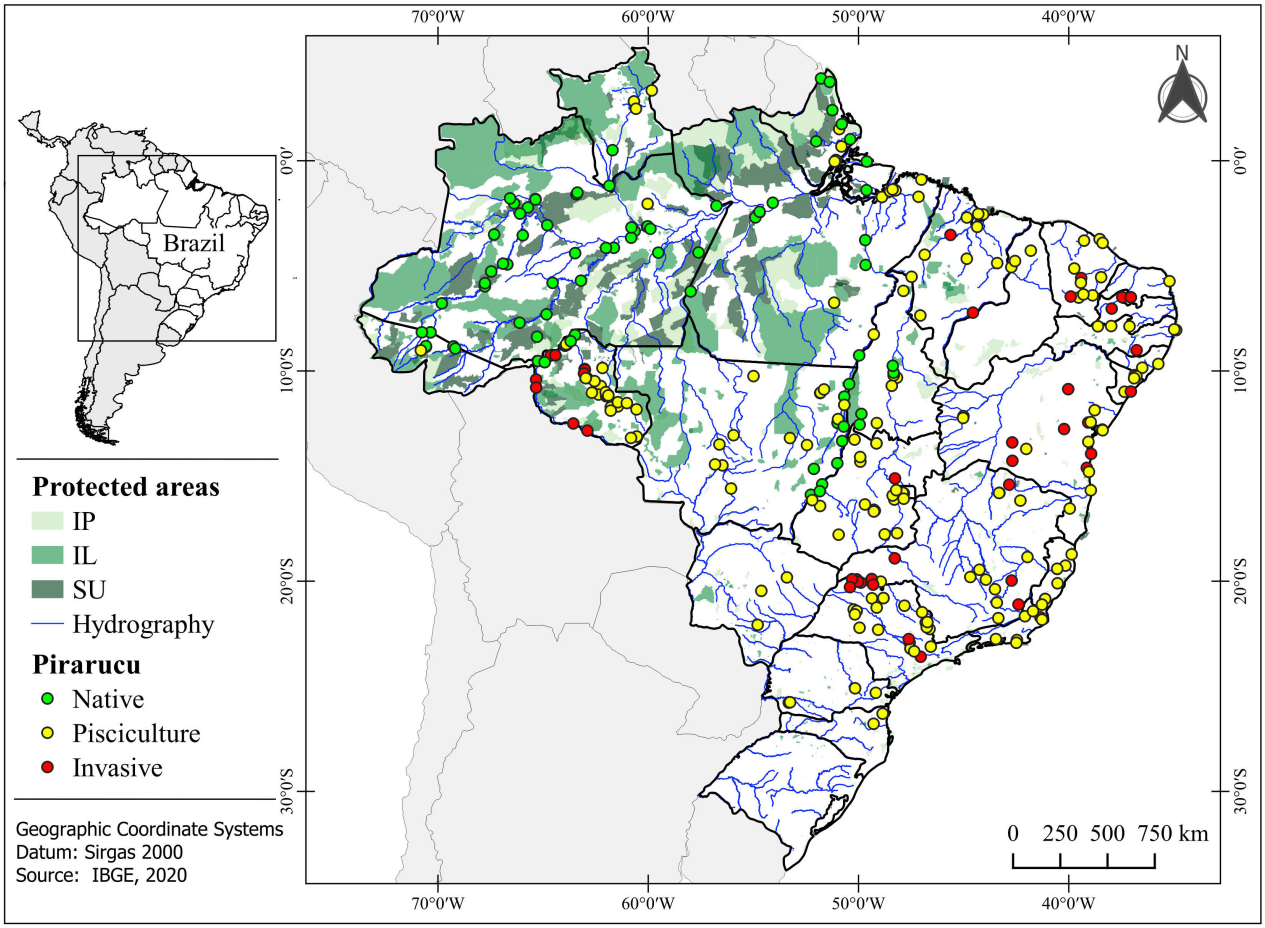

Figure 1. Thematic map of the spatial distribution of pirarucu (*Arapaima* spp.) in the Brazilian water network. IP = Conservation Units of integral protection, IL = Indigenous lands and SU = Conservation units of sustainable use.

articles and reports, as well as magazine and newspaper articles and other news media, which were located using the search tools available on the web, that the magnitude and spatial dispersion of pirarucu may still be underestimated (Figure 1).

According to Barroso et al. (2016), Brazil uses the same mechanisms employed in other countries to grant licenses for the breeding of aquatic animals, which follows FAO recommendations on biosafety (FAO 2016). However, the interpretation and practical application of these mechanisms when it comes to the production of exotic species are modified in accordance with the expertise and interests of each country, many of which already produce non-native species in captivity or seek their introduction and, after a few years, categorize these species as domesticated or already naturalized exotic species.

In addition, the disorderly exploitation of pirarucu since the Portuguese colonization has resulted in overfishing and the need to adopt regulations to prevent its extinction (Veríssimo 1895; IBAMA 1991, 1996; Isaac et al. 1996). The actions aimed at the conservation of pirarucu were focused on studies calling for the implementation of a community management methodology, developed and implemented in the late 90s by Leandro

Castello in the Sustainable Development Reserve of Mamirauá (RDSM) in the interior of the Amazon. After the success of this program, it was disseminated to other regions of Brazil and to neighboring countries (Castello 2004; Viana et al. 2007; Sousa et al. 2017). However, the supply of pirarucu in the market remained below the demand. This, coupled with the expansion of aquatic management areas, stimulated research aimed at improving captive breeding technologies for the species (Amaral et al. 2011).

In the municipality of Manoel Urbano in the state of Acre, the management of pirarucu has contributed positive results, with an increase in income related to pirarucu of approximately 270%, in addition to the improved conservation of aquatic ecosystems. The number of pirarucu in the managed lakes grew by about 90% in just four years, and a quadrupling of the productivity of the species in Lake Santo Antônio (WWF 2011, see reference in Appendix 1) is expected, after the fishers decided to temporarily forbid the capture of the pirarucu because of over-fishing. This should ensure that the population of this species rises from 60 to 190 individuals in just two years (WWF 2011, see reference in Appendix 1).

Currently the farming of pirarucu is considered to be a growing market segment of great potential. As such, some Brazilian states, with the consent of the wildlife protection bodies and the support of educational and research institutions, have been investing in rearing pirarucu in captivity (Rosa et al. 2020; Oliveira 2020), which has resulted in it becoming the eighth most produced species in the country, with an estimated production of 4.2 thousand tonnes in 2017 (Brandão et al. 2008; IBGE 2019).

Farming of pirarucu brings with it the risk of the fish becoming established in the local ecosystem. In the state of São Paulo, for example, catches of pirarucu have been reported since 2014 in seven municipalities near the border with Minas Gerais, with specimens ranging from 25 to 80 kilos. These were caught in the Marinheiro and Grande rivers, and the records include photographs of litters of pirarucu fry swimming over their parents, which indicates that the species has been reproducing normally in these locations and has managed to adapt to the climate of the southeast region (Santana 2015, 2018; Diário de Votuporanga (2019), and O Extra 2020, see references in Appendix 1). There are also reports that professional fishers are catching young fish to sell to the aquarium trade (Santana 2018, see reference in Appendix 1).

Catâneo (2019), Doria et al. (2020) and Sousa et al. (2021) reported the occurrence of pirarucu in locations upstream of the Santo Antônio hydroelectric power plant in Madeira River (Rondônia State in Brazil), though it is a non-native species in these areas due to the existence of pre-damming geographical barriers. The occurrence of pirarucu in this region was associated with the flooding of fish farms in Bolivia, Peru and/or

Rondônia-Brazil. In addition, there is a report of an accident occurring during the transport of pirarucu fry being smuggled over the border, which resulted in the escape of thousands of fry into the Mamoré River, constituting an example of an inadvertent accidental release.

The success of the introduction, establishment of, and invasion by pirarucu

The distribution of pirarucu in Brazil is the direct result of a program for the captive breeding of pirarucu outside its area of natural occurrence, which was initiated in Fortaleza, Ceará, in northeastern Brazil with the encouragement of the National Department of Works against Droughts (DNOCS) in 1939. According to Girão (2007), in 1940, a total of 5,590 juvenile pirarucu were introduced into some of the reservoirs in Ayres de Souza (Ceará), General Sampaio (Ceará), Riacho do Sangue (Ceará), São Gonçalo (Paraiba), Engenheiro Avid (Paraiba), Estevam Marinho/Mão d'água (Paraiba) and Itans (Rio Grande do Norte) with the express aim of controlling populations of undesirable fish species, piranhas and pirambebas (*Serrasalmus* spp.), in particular, that had proliferated in the reservoirs of the region (Fontenele and Vasconcelos 1982; Paiva and Mesquita 2013).

In conjunction with this activity, studies on the reproductive biology of the species were developed. The results indicated the potential viability of extensive cultivation at different stages of the life cycle, culminating with the observation of the first natural spawning in 1944, four years after the introduction pirarucu in the Riacho reservoir. Initiation of natural reproduction of individuals in Solonópolis, in the state of Ceará, when the survivors were approximately four years old, demonstrated their adaptation to the new habitat (Fontenele 1948; Fontenele and Vasconcelos 1982; Levis et al. 2013).

Other Brazilian states adopted the same practices and currently the pirarucu can be considered a species with a wide distribution in Brazil. Farming of pirarucu has been successful because the species possesses several characteristics favorable for its cultivation. These include: i) the fact that production can be carried out in different systems using different breeding modalities, ii) pirarucu can tolerate high stocking densities, in part because they can tolerate high levels of ammonia in the water; iii) pirarucu uses different breathing systems at different stages of growth (aquatic in the fry phase and aerial in the breeding phase), which reduces the risk to production under conditions of low oxygen concentrations; iv) pirarucu displays rapid growth, reaching 7 to 13 kg in the first 12 to 18 months of breeding, depending on the technology adopted, and, overall, can reach high biomass values; v) sexual maturation occurs early in the life-cycle, between the 4th and the 5th year of life (1.60–1.85 m and 40–45 kg), with the possibility of reproducing more than once a year if conditions are favorable; vi) there is a degree of parental care that results in a higher survival rate among the offspring; vii) pirarucu accepts commercial feed

designed for carnivorous fish and has a food conversion rate of approximately 2:1 of 1.5:1 when supplemented with live fish; viii) pirarucu has a high commercial value and a favorable market with large national and foreign demand; ix) the meat of the pirarucu is considered to be of high quality, with a light flavor, firm texture, no bones, and a low fat content; x) the overall average yield of carcass is around 57%, with a high yield of fillets (over 45%); xi) additional potential sources of revenue include its scales, which can be used as a raw material in handicrafts, its tongue, which can be used as sandpaper, and its skin, which can be used for the production of shoes, garments and other utensils (Fontenele 1948; Imbiriba et al. 1985; Neves 1995; Imbiriba 2001; Pereira-Filho et al. 2003; Ono et al. 2004; Oliveira et al. 2012; Ono and Kehdi 2013; Lima et al. 2015; Sousa et al. 2017; Rosa et al. 2020).

In spite of these benefits, the establishment and dissemination of non-native pirarucu can result in a biological invasion and pose a threat to the environment. Some of the same characteristics that make it desirable in aquaculture, especially its ability to tolerate a range of conditions and easily adapt to new environments, when coupled with the fact that it is a top-of-the-chain predator that feeds on other fish of commercial interest, increase its level of threat to the economy and the ecosystem. Therefore, the introduction of pirarucu in basins throughout Brazil will, in all likelihood, become one of the main sources of crises in local biodiversity, with the risk of extinction of populations of rare and often unique native fish, and increasing the biological similarity of diverse basins over time, i.e., biotic homogeneity. According to Olden et al. (2004) and Liu et al. (2017), the diversity crisis is a global problem responsible for the dramatic reconfiguration of modern ecosystems.

To aggravate the situation, according to Freitas and Serrano Jr. (2011) and Moraes et al. (2017), programs aimed at the eradication of invasive species in Brazil tend to be onerous and do not actually prevent the introduction of invasive species. Effective management plans need to be developed from the perspective of the principle of precaution and prevention as provided for in environmental law and then effectively applied in order to avoid the dissemination *Arapaima* spp. outside the Brazilian Amazon basin.

Risk assessment and ecological consequences

Despite its relevance, existing information on the occurrences of pirarucu in Brazilian watersheds can be considered limited (Table S1) in view of the expansion of the pisciculture industry and the national dissemination of breeding programs for the species. In many Brazilian basins, the pirarucu is considered an invasive species (non-native) that has been established intra-country, i.e., it has undergone successful introduction between regions of the country (Carvalho et al. 2015; Casimiro et al. 2018; Doria et

al. 2020; Pereira et al. 2021). In this context, the scarcity and inconsistency of the information regarding the locations and the real risks of introduction compromise conservation efforts.

The negative impacts caused by the introduction of non-native fish species into Brazilian aquatic ecosystems have already been documented by Vitule et al. (2012), Daga et al. (2015), Frehse et al. (2016) and Padial et al. (2017). Among the impacts that the introduction (accidental or intentional) of species in a new environment cause, we can cite threats to biodiversity due to the absence of natural predators, with the possibility of extinctions of vertebrate species, biotic homogenization, reduction of natural genetic variability, hybridization with a risk of fertile individuals, introduction of pathogens, trophic changes, competition for resources, the possibility of a population explosion and colonization of contiguous environments, in addition to economically affecting the families of fishers and other participants in the fishery production chain (Agostinho and Júlio Jr. 1996; Delariva and Agostinho 1999; Agostinho et al. 2005; Hermoso et al. 2011; Lima and Batista 2012; Bellard et al. 2016).

The need for rigor in the control and monitoring of fish farming systems involving the cultivation of pirarucu, especially in tropical regions, was highlighted by Pereira et al. (2021) as a means of mitigating the risk of dispersion and invasion of *Arapaima* spp. into natural environments and the potential impacts of introduced pirarucu on the assemblage of native species in the environment. Despite the CONAMA Resolution No. 413/2009, Law Nº. 11,959/2009, IBAMA Decree Nº. 27/2003 and other regulations aimed at environmental licensing of aquaculture in order to establish limits on the rearing of exotic and allochthonous species and to spell out the responsibility of aquaculture farmers for containment mechanisms that would prevent captive organisms from gaining access to the drainage waters of the Brazilian watershed, limited supervision of farmers' compliance with these regulations remains a problem in Brazil.

Conclusions

From what we have seen, it is understood that the pirarucu has become established in much of Brazil's territory, and is recognized as a promising species for the consumer market. However, it occupies several bodies of water in a variety of drainage basins outside of its native range and, therefore, poses a great threat to the diversity of native fish species. This threat must be avoided at all costs, but principally through population control of invasive pirarucu, if we wish to maintain the sustainability of native fish stocks in Brazil for future generations. Finally, ignorance of or understimates of the risks of intra-country introduction and spread of pirarucu and other species outside their native ranges influences how we count non-native species and invasions and how we perceive the impacts of their presence. This is especially risky in the case of pirarucu given the

threats associated this emblematic native species and its potential impacts on the unparalleled biodiversity of a country like Brazil.

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Authors' contribution

RGCS: Research conceptualization; sample design and methodology; data analysis and interpretation; roles/writing – original draft; writing – review and editing. LSP: Research conceptualization; sample design and methodology; investigation and data collection; roles/writing – original draft; writing – review and editing. MAC: Research conceptualization; sample design and methodology; investigation and data collection. CECF: Research conceptualization; sample design and methodology, roles/writing – original draft; writing – review and editing. MDAM: Sample design and methodology; data analysis and interpretation; roles/writing – original draft; writing – review and editing. DMZ: Research conceptualization; sample design and methodology; roles/writing – original draft; writing – review and editing. CHFJ: Research conceptualization; sample design and methodology; roles/writing – original draft; writing – review and editing. LC: Research conceptualization; sample design and methodology; roles/writing – original draft; writing – review and editing. JRSV: Research conceptualization; sample design and methodology; roles/writing – original draft; writing – review and editing.

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Supplementary material

The following supplementary material is available for this article:

Table S1. Records of *Arapaima* spp. in the Brazilian water network.
Appendix 1. References to Table S1.