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THE AMAZONIAN *Arapaima* CHANGES ITS STATUS FROM THREATENED SPECIES TO AN INVADER OF EARTH'S FRESHWATER ECOSYSTEMS

Pirarucu muda seu status de espécie ameaçada para invasora dos ecossistemas de água doce do planeta

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ABSTRACT

A survey of the records was conducted regarding the locations on the planet in which *Arapaima* has been introduced from its natural habitats in areas of South America, whether for aquaculture or the aquarium trade. Originally, the global expansion of this species was intended to maintain its existence in the face of a perceived risk of extinction. However, the results of the intended and accidental spread of its distribution reveal that *Arapaima* is an invasive species that can endanger native fish species diversity. It is an air breather, which allows it to inhabit low oxygen conditions of warm tropical water, and a species that grows fast, attaining a large size when mature. It also presents parental care and is a generalist predator that feeds on many other species. Furthermore, it can escape from managed fish farms into natural waterways and establish viable populations without control. From the literature, 228 sites with records of *Arapaima* from around the world were identified, 95 of which are native sites for the species and 133 are sites where they were introduced. These sites are distributed in 28 countries in the Americas (North, Central and South), Europe, and Asia. Published results of introductions reveal that *Arapaima* has had negative impacts on native fish species, thus warranting closer attention in regards to how, when and where this species should be allowed.

Keywords: aquaculture, aquariophilia, invasive species, pirarucu, tropical biodiversity.

RESUMO

Foi realizado um levantamento dos registros sobre os locais no planeta onde o pirarucu *Arapaima* foi introduzido a partir de seus habitats naturais em áreas da América do Sul, seja para a aquicultura ou para o comércio de aquários. Originalmente, a expansão global desta espécie tinha como objetivo manter sua existência, diante de um eminente risco de extinção. No entanto, os resultados da propagação programada e acidental de sua distribuição revelaram que o *Arapaima* é uma espécie invasora que pode colocar em risco a diversidade de espécies de peixes nativos. É um peixe com respiração aérea, isso lhe permite viver em baixas concentrações de oxigênio em água tropical, cresce rapidamente, atinge um grande porte quando adultos, apresenta cuidado parental, e é um predador generalista que se alimenta de muitas outras espécies. Além disso, pode escapar das pisciculturas indo para os cursos d'água naturais e estabelecem populações viáveis sem controle. Assim, foram identificados a partir da literatura 228 locais com registros de pirarucu em todo o mundo, sendo 95 locais onde são nativos e 133 locais onde foram introduzidos, estão distribuídos em 28 países das Américas (Norte, Central e Sul), Europa e Ásia. Resultados publicados de introduções revelam que o *Arapaima* apresentou impactos negativos sobre as espécies de peixes nativos, o que requer maior atenção em como, quando e onde essa espécie deve ser permitida.

Palavras-chave: aquacultura, aquariofilia, espécies invasoras, pirarucu, biodiversidade tropical.

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INTRODUCTION

Arapaima gigas (Schinz, 1822), known as *paiche* in Peru, Ecuador, Venezuela and Bolivia, and as *pirarucu* in Brazil and Colombia (Carvajal-Vallejos et al. 2011), is the Amazon region's largest freshwater fish (Arantes et al. 2010). It presents parental care and grows very quickly (Arantes et al. 2006; Arantes et al. 2010; Campos-Silva et al. 2019), attaining an adult size of up to 3 m in length and over 200 kg in weight, thus placing it among the largest scaled freshwater fish in the world (Stewart 2013a; Stone 2007). It occupies the top of the aquatic food chain as a "generalist predator" omnivore/piscivore (Sánchez 1969; Queiroz 2000; Watson et al. 2013; Kumar et al. 2019) and is also an obligate air-breather (Schmidt-Nielsen 1997). Since the mid-nineteenth century, the genus *Arapaima* has been classified as monospecific, comprising only the species *Arapaima gigas* (Reis et al. 2003). Some more recent studies have presented records of distinct characteristics among captured pirarucu, thereby adding four putative species to the genus *Arapaima*: *A. arapaima, A. mapae, A. agassizii* and *A. leptosoma* (Stewart 2013a, b). However, more recent genetic analysis of *Arapaima* that were sampled from spatially separate populations in the Amazon basin has found no evidence of multiple species (Farias et al. 2019). In order to avoid this controversy, we will simply refer to the genus *Arapaima* for the remainder of this paper.

Arapaima is native to the floodplains in the Amazon and Essequibo basins, with natural distribution in Brazil, Peru, Colombia, Ecuador and British Guyana (Migdalski 1957; Barriga 1986; Hrbek et al. 2007; Castello and Stewart 2010; FAO 2020) and occupies most lotic environments with a weak current, including flooded forests, rivers, lakes, areas below barriers, such as waterfalls and rapids, and some coastal drainage basins of Brazil. The geographical distribution of this species in northern South America is limited by geographical barriers such as waterfalls and river rapids, which have strong current and prevent their passage (Queiroz and Sardinha 1999; Castello 2008; Castello and Stewart 2010). However, as an air breather it is able to survive and flourish in hypoxic habitats of floodplains of the Amazon basin (Arantes et al. 2010).

Arapaima has good market value, largely due to its tender, flavorful meat and few bones (Hrbek et al. 2007). There was great demand in the consumer market in the mid-70s, which caused overfishing and a drastic decline in *Arapaima* populations that inhabit southwestern Guyana, the lower and middle Amazon River and adjacent floodplains (Carvajal-Vallejos et al. 2011; Watson et al. 2016). This fast decline resulted in its classification as "endangered" in the list of protected species in Appendix II of the Convention on International Trade in Species of Wild Flora and Fauna (Mueller 2005; Viana et al. 2007).

In 1996, with little evidence of the recovery of *Arapaima* stocks in the Amazon region, the Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA) prohibited its capture from the wild in the state of Amazonas, and allowed sale of only individuals raised in managed areas or from aquaculture farms (Castello et al. 2009; Campos-Silva et al. 2019). Nevertheless, after the implementation of a co-management strategy (called lake management systems), which established annual catch quotas defined from previous estimates of abundance, the natural stocks of *Arapaima* recovered sufficiently for the species to be removed from the list of endangered fish (MPA 2011).

With the return of viable stocks in the natural environment, and with the aim of avoiding its return to endangered status, *Arapaima* was introduced to areas of the Amazon that had no natural *Arapaima* populations, and to other regions of the world, both for aquaculture of edible fish and for the aquarium trade (Pelicice et al. 2014; FAO 2020). Unfortunately, this generalist predator proved to be invasive (Queiroz 2000; Winemiller 2005), and able to colonize slow-flowing rivers and floodplains through lateral migration (Castello 2008) at a rate of up to 10 km/year (Castello et al. 2011; Campos-Silva et al. 2019).

The invasion of aquatic environments by exotic species is an environmental problem that has been reported in several countries (Vitule 2009; Ellender and Weyl 2014; Bezerra et al. 2019; Doria et al. 2021), and justifies the inclusion of the precautionary principle in the planning of new fish introductions in sensitive aquatic ecosystems (Van Damme et al. 2013). Invasive fish species are considered one of the main causes of extinction of fish populations in freshwater systems (Sala et al. 2000; Bezerra et al. 2019), and thus become an eminent threat to the planet's ecosystems and biodiversity (Leprieur et al. 2009; Vitule et al. 2009; Cucherousset and Olden 2011; Vitule et al. 2012). This was exemplified in India, where more than 60 species of fish became extinct in the twentieth century, and approximately 20% of this total was due to the introduction of exotic species (Colautti et al. 2006a, 2006b; Raghavan 2019; Raj et al. 2021). In 2018, in the Indian state of Kerala, a large flood occurred that caused the escape of *Arapaima* into flooded areas, where it then settled and is currently considered one of the top predators of the food chain (Raj et al. 2021). As a result, it is now a great threat to the biodiversity of native fish of this region (Raghavan 2019). *Arapaima* also was introduced into Malaysia through the ornamental fish industry (Rixon et al. 2005; Rahim et al.

2013), and has caused economic damage to local fisheries through the predation of native fish stocks and the destruction of fishing nets (Khairul 2012).

In Brazil, *Arapaima* was first found outside its native region in the lower Mamoré River, municipality of Guajará Mirim (Doria and Brasil 2012), and was moving in the direction of the headwaters of the Madeira River in the 1960s (Van Damme et al. 2015) after having probably escaped from newly installed fish farms near Puerto Maldonado, Peru and other farms in Bolivian waters (Carvajal-Vallejos et al. 2011). This led to a drastic decrease in stocks of other fish species in the northwestern region of the Bolivian Amazon (Carvajal-Vallejos et al. 2011; Miranda-Chumacero et al. 2012), similar to what occurred in the Paranapanema River, in southern Brazil (Casimiro et al. 2018). The release of *Arapaima* in non-native areas of Bolivia has ensured its economic importance in fisheries (Van Damme et al. 2015). The record for fish landings in these areas was 258 tonnes of *Arapaima* harvested in 2007 (Van Damme et al. 2015). On the other hand, these introduced predators have been blamed for reducing the abundance of native characids in the fishing areas of indigenous riverine communities that relied on these smaller fish for subsistence (Van Damme et al. 2015).

The main cause of the introduction of exotic and invasive species in non-indigenous regions or new environments where they were not intentionally introduced is the escape of fish from farming systems that are precarious because there are generally no barriers to prevent the escape or dispersal of managed fish species (Garcia et al. 2018). Escape is facilitated by these aquaculture enterprises that often are built within, or very close to natural drainage basins (Raghavan 2019), and it can be intensified by an atypical flood that facilitates the spreading of *Arapaima* into the adjacent flood plains areas (Casimiro et al. 2018; Doria et al. 2020). Given the above, a survey of records of the locations where the introduction of *Arapaima* occurred in natural and artificial environments around the world was carried out in order to show that the genus *Arapaima* is an invasive species and a current threat to the diversity of native fish species.

MATERIALS AND METHODS

Harzing Software was used to search databases of the Scientific Electronic Library Online (Scielo) and Google Scholar. Papers published between 2005 and 2021 were included when they used the keywords invasive, alien and non-native fish, or *Arapaima*. All records of *Arapaima* in natural environments and in captivity, including fish farming and aquariums were included. Our search and selection methods yielded an extensive list of citations that formed the corpus of the study. The distribution points of *Arapaima* from around the world were inserted into Google Earth to obtain coordinates that were used to generate a spreadsheet with the locations (often with details of rivers, lakes and fish farms), geographical coordinates, procedure of introduction, sources of origin for the information, and a map using the geoprocessing software ArcGIS. For the data analysis, the descriptive statistics were used to quantify the absolute and relative frequency of *Arapaima* locations.

RESULTS

Current distribution of Arapaima around the planet

In all, 228 sites were found in which *Arapaima* are present on the planet. These include 95 sites where they are native and 133 sites where they were introduced. *Arapaima* individuals were recorded in 28 countries distributed in the Americas (North, Central, and South), Europe, Africa and Asia. The survey revealed the status of *Arapaima* in several parts of the world, evidencing its success as invader in areas of low latitudes (Figure 1).

In the Americas

Arapaima have been recorded in three countries on the North American continent. In the United States, they are held in facilities for research at the University of Florida, at UF/IFAS Tropical Aquaculture Laboratory, Ruskin, Hillsborough County, where researchers assess the risk of rearing *Arapaima* on fish farms in the state (Buck 2016). In addition, pirarucu were found in public aquariums such as the Tarpon Zoo in Florida, in the Smithsonian National Zoo in Washington, in the Shedd Aquarium in Chicago, Omaha's Henry Doorly Zoo and Aquarium (Nebraska), in the Tennessee Aquarium, in the Pittsburgh Zoo, PPG Aquarium in Pennsylvania, and in the Georgia Aquarium in Atlanta, Georgia.

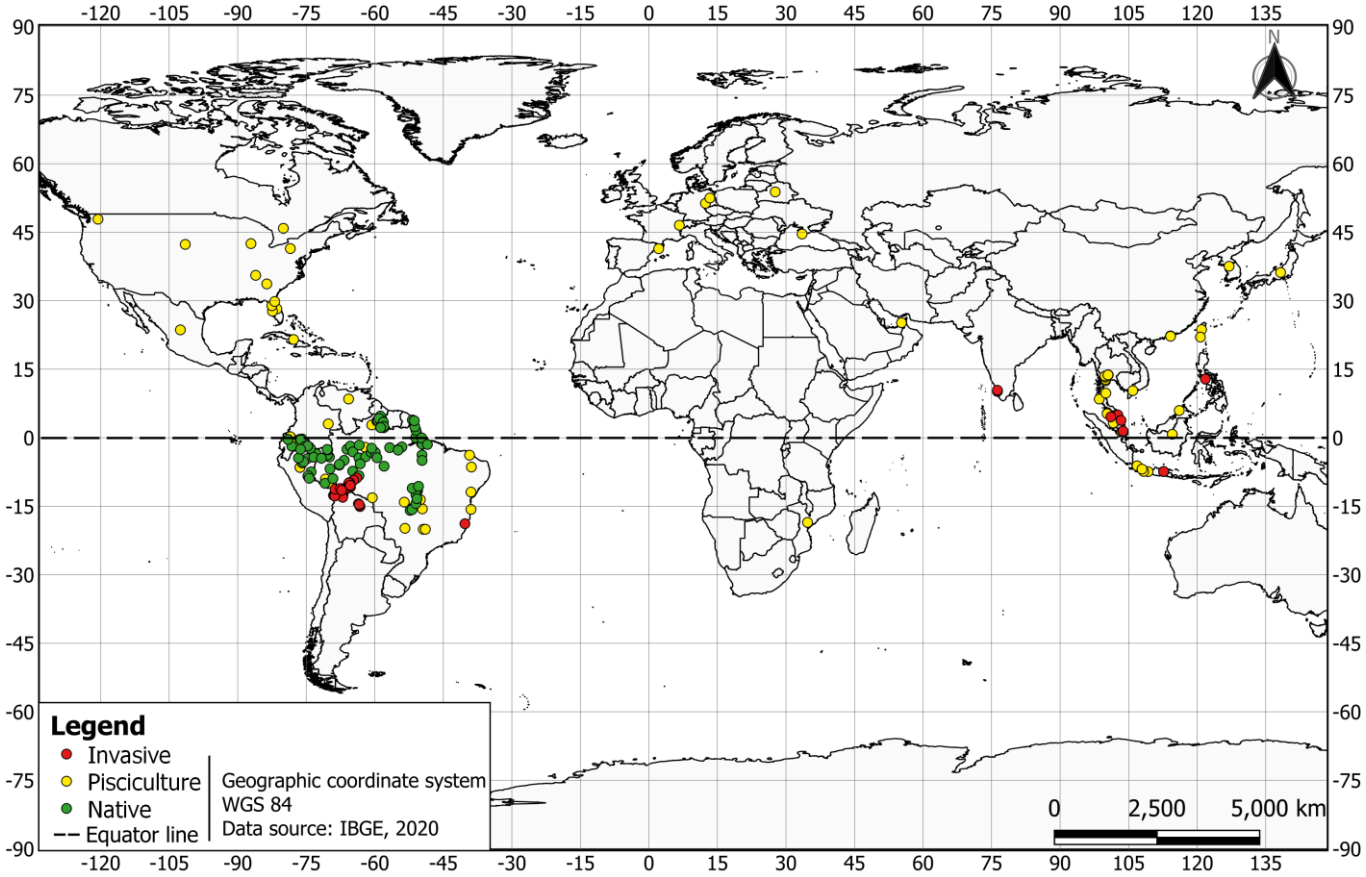

Figure 1. Geographical location of the breeding and capture sites of pirarucu in natural environments and in captivity.

In 1985, captures of *Arapaima* were carried out at the Miami International airport, Florida (Hance 2013, iNaturalist 2021; GBIF 2021). In Canada the species was reported in the Ripley's Aquarium of Canada, in Toronto. In Mexico, *Arapaima* was brought from Brazil in 1964 with the aim of farming it. However, due to the intolerance of *Arapaima* to low temperatures, that attempt was unsuccessful (Welcome 1988; FAO 2020). In Central America, *Arapaima* that originated from Peru in 1973 and 1982 were introduced into the Republic of Cuba (northern Caribbean) for the purpose of cultivation for commercial fishing, and are being reproduced in captivity (Welcome 1988; FAO 2020).

Arapaima are recorded in 130 locations in South America, where it is classified as native to countries such as Peru, Brazil, Colombia, Ecuador and Guyana (Barriga 1986; García-Dávila et al. 2018; Campos-Silva et al. 2019). Of this total, the species was introduced to 47 locations, of which 17 are in Peru (Hrbek et al. 2007; García-Dávila et al. 2018; Farias et al. 2019). About 1,000 individuals were introduced for fish farming in lakes Valencia and Sandoval in the Madre de Dios region of Peru in 1979 (Miranda-Chumacero et al. 2012). There are reports of an escape after a large flood, and these fish were reported for the first time outside the breeding lakes in the mid-1980s, with records of these individuals in the border area with Bolivia in the 1990s (Miranda-Chumacero et al. 2012).

In Bolivia, 36 distribution areas of the *Arapaima*, including the Pando region in the watershed of the Madre de Dios River, have been identified (Miranda-Chumacero et al. 2012). In Brazil, 53 areas of introduction of *Arapaima* were identified, accounting for 15 states: Roraima, Amapá, Acre, Amazonas, Rondônia, Mato Grasso, Mato Grasso do Sul, Goiás, Pará, Tocantins, Ceará, Bahia, São Paulo, Minas Gerais and Espirito Santo, where a pirarucu was recently caught in the Itapemirim River near Cachoeiro de Itapemirim and which weighed about 50 kg (Hrbek et al. 2007; Amaral 2007; Ono 2011; Kubitza et al. 2012; Borges et al. 2013; Marinho 2013; Carvalho 2015; Farias et al. 2019; Sea Food Brasil 2019; Doria et al. 2020; Paula 2021).

In Colombia, populations of *Arapaima* were found in the floodplains near Leticia, as well as on a fish farm raising pirarucu in Puerto López (Hrbek et al. 2007; GBIF 2021), and in Guyana, located in the upper part of the Essequibo Basin (Watson et al. 2016). In Ecuador, populations of *Arapaima* were located in four rivers: the Cuyabeno, Aguarico, Napo and Tiputini; in the Wildlife Center Ecolodge and Fish Farm near Nueva Loja (Barriga 1986; Reuters 2019; GBIF 2021).

IN EUROPE

On the European continent, six *Arapaima* were reported in some public aquariums situated in the countries Spain, Germany (Leipzig and Berlin), Switzerland, Belarus and the Ukraine (Stewart 2013a; iNaturalist 2021).

IN ASIA

In Taiwan, *Arapaima* is highly appreciated by aquarists and sport fishermen, and has been classified as the fourth most common destination for exporters of live *Arapaima*; most from the markets of Brazil, Colombia and Peru, with 11,608 fish exported since 1982. It has also been distributed in Thailand and Indonesia. Currently, *Arapaima* are still being farmed in these locations. However, in 2001, just 1,800 juvenile *Arapaima* were imported to Taiwan from South American countries (Mueller 2005). In Indonesia, *Arapaima* are bred in natural ponds and in the Brantas River basin (Mueller 2005; Zakaria 2017; Fadjar et al. 2019).

Among the Asian countries, Japan is the largest importer of live *Arapaima*, and has been since 1977, followed by China (Mueller 2005). In China, most importers of live *Arapaima* were in Hong Kong and fish were introduced for aquariums and fish farms there as well in other parts of the country (Mueller 2005). In 2018, in the Kerala region of India, *Arapaima* escaped from fish farms and colonized the Periyar, Muvattupuzha, Kurumali and Chalakkudy Rivers, where they are now frequently caught (Kumar et al. 2019). In Malaysia, there are records of the presence of *Arapaima* in the Terengganu, Pahang, Johor and Perak Rivers (Zakaria 2017). In the Philippines, *Arapaima* was introduced in 1992 for the aquarium trade and today inhabit several natural environments in the country (FAO 2020). The presence of *Arapaima* has been reported in countries such as Dubai (United Arab Emirates), Vietnam, Singapore and South Korea, where it is commonly found in public aquariums or in places reserved for sport fishing activities (Cassiano et al. 2008, Mahmud 2019, FAO 2020, iNaturalist 2021). All records of *Arapaima* are listed in the Appendix I, including the geographical coordinates, mode/year of introduction and source (Appendix I, can be requested through the e-mail: raniregarcez@unir.br).

IN AFRICA

On this continent, despite the similarities between the tropical environments of the various African countries and some of the countries located in South America, where *Arapaima* has its natural origin, only one place was found throughout the African continent where the *Arapaima* are grown in nurseries with tilapia (*Oreochromis mossambicus*), and this was located in the Chicoa region of Mozambique (Gonzaga-Junior, M.A., personal communication*)

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* Marcondes Agostinho Gonzaga-Junior, Chief of the Department of Fisheries Engineering, Unir, Jun. 10, 2022.

DISCUSSION

Since the inclusion of *Arapaima* as an endangered species, many efforts have been made to ensure its existence in the natural environment; mainly through lake management systems and annual catch quotas (Castello et al. 2011; Campos-Silva et al. 2019). At the same time, there has been an increase in the cultivation of the *Arapaima* in aquaculture (Pelicice et al. 2014; FAO 2020), in many cases outside its native areas, including other continents. Simple failures or the effect of extreme floods were the principal causes of individual dispersal into non-native natural environments, and such events have been reported in a number of locations in Peru, Bolivia (Miranda-Chumacero et al. 2012), Brazil (Farias et al. 2019), India (Kumar et al. 2019; Raj et al. 2021) and Indonesia (Mueller 2005). The three largest exporters of live *Arapaima* are Brazil (the leader with 32% of total exports), followed by Colombia (21%) and Peru (16%) (Mueller 2005). The increase in the farming of *Arapaima* also has been driven by the aquarium trade (stimulated by the ornamental beauty of the fish and its cultural history), sport fishing (due to the large size and strength characteristics of the fish) and food (due to the distinct taste and high nutritional values of the meat), on the American, European and Asian continents.

Natural barriers such as waterfalls also limit the dispersal of *Arapaima* and prevent these animals from colonizing upstream environments (Castello and Stewart 2010). As a consequence, another point to be considered are the environmental changes that occur synergistically with the introduction, establishment and

spread of *Arapaima*. Removing natural barriers, such as waterfalls, could facilitate movements of *Arapaima* toward new areas. Doria et al. (2020) reported that the construction of two large hydropower dams in the middle channel of the Madeira River basin formed lentic habitats of weak current, which are favorable areas for dispersion and establishment of *Arapaima*.

Arapaima has not generated major concerns in Europe or North America regarding the invasiveness of this fish through possible escapes to natural environments, probably because of its intolerance to low temperatures. The ideal temperature for *Arapaima* is around 30 ºC (Ono and Kehdi 2013). In this regard, the success of its cultivation depends not only on the usual care, but also on a system with temperature control of the water in order to guarantee the minimum conditions for its survival. The sensitivity of *Arapaima* to the cold could provide an additional mitigating factor in a risk analysis associated to its introduction in Florida (Hill and Lawson 2015).

The results of our research suggest that there should be far greater rigor in the control and monitoring of fish farming systems that involve *Arapaima*. This is especially true in tropical countries (near the equatorial zone) in order to avoid or minimize the risks of dispersal of and invasion by *Arapaima* in natural environments that have environmental characteristics similar to their natural habitats. Furthermore, additional effort, probably through enforcement projects and educational programs, is recommended in order to avoid deliberate release in the natural environment by people aiming to improve recreational fishery. It also is necessary to alert fish traders and aquarists about the various risks offered by *Arapaima* to native species (often endemic) regarding the places where they are introduced, since when they grow too large for the aquarium they may be discarded by the owner into natural waterways.

In general, introduction of fish species has been made in developing countries to increase the food supply (Ortega et al. 2015; Bezerra et al. 2019). However, several impacts have been reported, including loss of biodiversity through the extinction of endemic species (Vitule et al. 2009; Goslan et al. 2010). The main impacts associated with the introduction of *Arapaima* in aquatic environments, where it is a non-native species, that have been documented and predicted, are derived from its functional characteristics. It is the largest scaled fish and a generalist predator (Queiroz 2000) and its introduction offers risks to the aquatic diversity due to direct predation. There are several studies that report the effects of introducing top predator species, such as the genus *Cichla*, which has been introduced to several parts of the Earth (Carvalho et al. 2014; Khaleel et al. 2021), and the most emblematic case of depletion of the native fish assemblage happened in Lake Gatun (Panama) (Sharpe et al. 2017); which involved the northern snakehead (*Channa argus*) that was introduced to North America, Asia and eastern Europe (Courtenay and Williams 2004; Fuller et al. 2012). Due its large size and behavior, in general, *Arapaima* has no natural predator other than man in areas where it is introduced, and fast populational growth and a high impact on prey populations should be expected.

The impact of introduction of *Arapaima* goes beyond the ecological aspects. Ten years after its introduction in Bolivian waters, it began to be found in the fish landings of towns of the Madre de Dios River basin (Carvajal-Vallejos et al. 2011, Miranda-Chumacero et al. 2012). In 2013, Carvajal-Vallejos et al. (2013) reported that *Arapaima* contributed to around 80% of the total fish landings in urban centers of the Madre de Dios River basin. There are also concerns regarding the presence of *Arapaima* in protected areas that are intended to protect endemic or especially vulnerable species, but there are no data describing such type of impact. Finally, changes in the commercial chain of fish and in the socioeconomic relationships between commercial fishers and riverine people has been reported, including involving indigenous people, since some lakes where the exploitation occurs are located in indigenous reserves.

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