Management of Biological Invasions (2015) Volume 6, Issue 4: 375–383
doi: http://dx.doi.org/10.3391/mbi.2015.6.4.06


**Research Article**

# The expansion of *Arapaima* cf. *gigas* (Osteoglossiformes: Arapaimidae) in the Bolivian Amazon as informed by citizen and formal science

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Received: 7 July 2014 / Accepted: 30 June 2015 / Published online: 29 July 2015

*Handling editor*: Kit Magellan

## Abstract

The giant osteoglossomorph fish *Arapaima* cf. *gigas* was introduced to the northern Bolivian Amazon over a half century ago and now contributes significantly to commercial fisheries. Despite this, little is known regarding its current distribution and invasion potential. Here, we address this knowledge gap using two complementary methods: interviewing key informants and examining fisheries landing records in the principal landing site (Riberalta). Both interviews and landing data revealed that the species represents approximately 50% of the total commercial catches, and that it now occupies approximately 340 km$^2$ of floodplain lakes in the Beni, Orthon and Madre de Dios River basins. The annual yield is estimated at 258 t, equivalent to 0.76 kg/ha/year. The current geographic distribution represents approximately one-quarter (24%) of floodplain lakes in the lower Bolivian Amazon, suggesting high fisheries potential of the species if it would also colonize the remaining Mamoré and Iténez River basins. The potential for negative ecosystem impacts of the *A.* cf. *gigas* invasion seems likely, considering the large body size, life history and feeding ecology of this species, but has not yet been clearly demonstrated. Factors that might limit further expansion are natural barriers (waterfalls) in the lower Mamoré, and periodic cold temperature conditions in the Mamoré and Iténez River basins.

**Key words:** fish, bony tongue, introduced species, artisanal fisheries, Upper Madera River, Riberalta

## Introduction

Inland fisheries provide a vital source of commerce, employment and nutrition for people throughout the world (Welcomme et al. 2010). This is particularly true in subsistence and artisanal fisheries in developing nations, where inland fishing activities are an integral part of a diversified livelihood, playing a critical role in the food security of producers and their families, as well as contributing to national and international economies. Many inland fisheries, particularly those of large tropical river basins, occur within species-rich, ecologically diverse assemblages where population dynamics are difficult to observe and interpret (Beard et al. 2011). Issues of over-exploitation, climate change, dams and the effects of other human-related threats on these fisheries are a continuing concern (Allan et al. 2005; Ficke et al. 2007; Castello et al. 2013). Non-native fish species are considered a critical threat to freshwater ecosystems (Leprieur et al. 2009; Vitule et al. 2009; Cucherousset and Olden 2011; Vitule et al. 2012), however these species can also support important targeted commercial and recreational fisheries (Eby et al. 2006; Gozlan 2008; Simberloff et al. 2013).

The Bolivian Amazon, consisting largely of the middle Madera River basin, supports over 800 fish species (Carvajal-Vallejos et al. 2014).

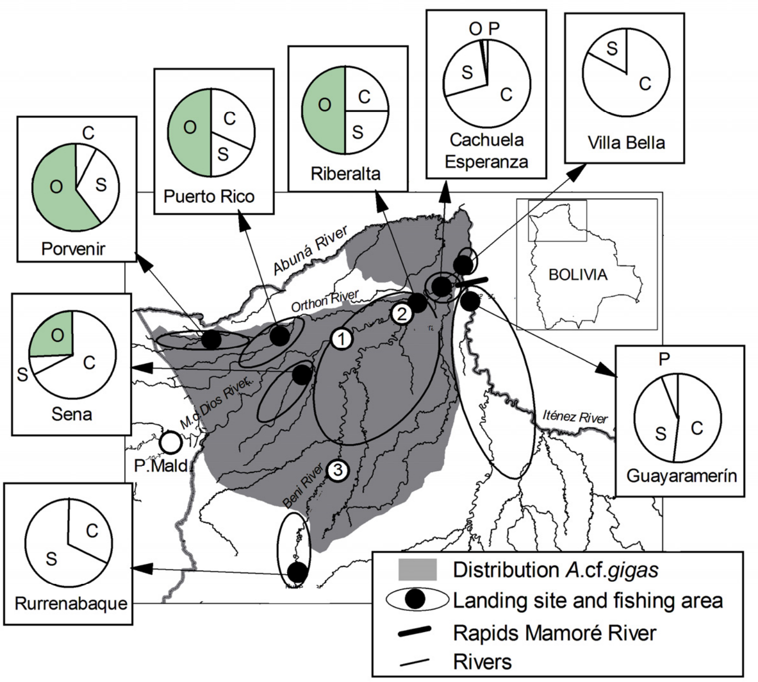


**Figure 1**. Relative percentage of fish taxa in the landings in the northern Amazon of Bolivia in 2008 according to interviews with key persons in seven landing sites. S = Siluriformes; O = Osteoglossiformes; C = Characiformes; P = Perciformes. Clupeiformes were not included. See Table 1 for detailed list of species within each of the taxa mentioned. The fishing areas are approximate. P.Mald. = Puerto Maldonado (Peru). ①②③ are points of first observation of *A*. cf. *gigas* (see Table 2).

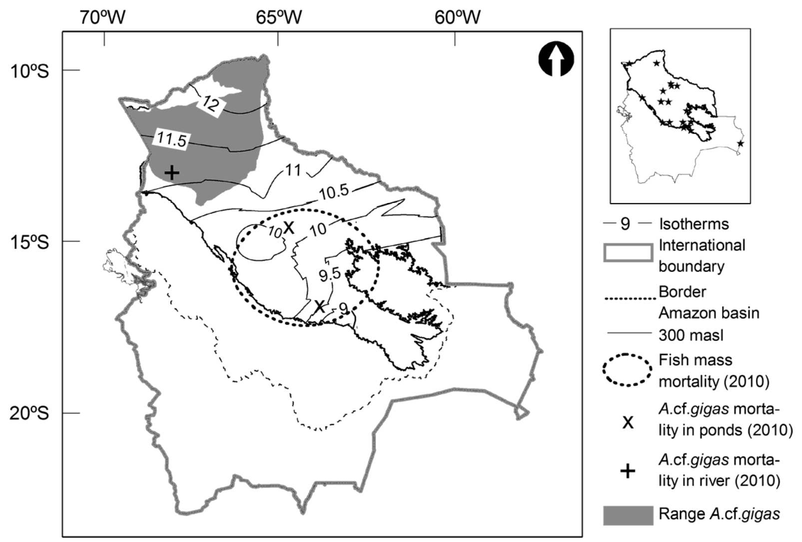


**Figure 2.** Map of minimum air temperatures in the Bolivian Amazon below 300 m above sea level (masl). Values were calculated averaging the four sequential coldest days of the year over 21 years (1990–2010), as recorded by SENAMHI weather stations. The map indicates localities where native species and *A*. cf. *gigas* mortality was reported in natural water bodies during a cold shock in July 2010.

The high species richness can be explained by significant habitat heterogeneity (Van Damme et al. 2011a) and historical isolation by high gradient rapids in the border area with Brazil. However, this isolation may change rapidly with the construction of hydropower dams and the increasing trade of species for aquaculture (Torrente-Vilara et al. 2011; Castello et al. 2013; Pelicice et al. 2014; Daga et al. 2014) and consequent risk of non-native species introductions. One of the first dramatic cases of species introductions is the invasion by *Arapaima* cf. *gigas* (Schinz, 1822) of the northwestern region of the Bolivian Amazon (Carvajal-Vallejos et al. 2011; Miranda-Chumacero et al. 2012) from intentional releases or aquaculture escapees in Peru.

*Arapaima* cf. *gigas*, called paiche in Peru, Ecuador, Venezuela and Bolivia, and pirarucú in Brazil and Colombia (Carvajal-Vallejos et al. 2011), is a large (up to 3 m length and 200 kg) air-breathing predator that historically dominated floodplain lake systems of the tropical central Amazon (Migdalski 1957; Arantes et al. 2010). An ancient Osteoglossomorph fish species, with its closest relative in Africa, paiche is one of the world's largest fish with scales. Recent work has suggested that the species could actually consist of several species (Stewart 2013). In this paper we thus use the *A.* cf *gigas* nomenclature, pending resolution of the fish's true identity.

In its native Brazil, Peru, and Colombia, paiche has long been utilized by indigenous peoples (Sánchez 1960), with a substantial increased exploitation with the advent of European colonists (Goulding 1980) and an appreciation of the animal's firm flesh, giant slabs of meat, and lack of intramuscular bones – marketed as salted and dried fillets (Hrbek et al. 2007). The advent of nylon gill nets and ice increased the fishery substantially, so that by the 1980s there was dramatic decline of *A.* cf. *gigas* populations in the lower and middle Amazon. As a result, the fish was indexed in Appendix II of the international conservation treaty Commercial Species of Wild Fauna and Flora (Carvajal-Vallejos et al. 2011). Brazil eventually responded to this crisis in 1996 and closed the fishery entirely for several years, subsequently allowing only selected community-managed lake fisheries that implemented a management plan for this species (Castello et al. 2009).

Although its range may have been substantially greater in geological time, recent native distribution in the Amazon of the species does not include Bolivia. Presumably, the rapids downstream of Cachuela Esperanza in the Beni River and Guayaramerín in the Mamoré River (Figure 1) formed barriers to natural upstream range extension (Carvajal-Vallejos et al. 2011; Torrente-Vilara et al. 2011). The species is listed as Data Deficient (DD) according to the IUCN Red List of Threatened Species.

*Arapaima* cf. *gigas* was first found in the upper headwaters of the Madera in the 1960s; a probable outcome of escapees from Peruvian incipient aquaculture facilities around Puerto Maldonado. Over the last half century, the species has spread downstream into Bolivian waters (Madre de Dios watershed). The earliest record of *A.* cf. *gigas* in the Bolivian fisheries was in 1975 (Carvajal-Vallejos et al. 2011), but official fisheries statistics from 1982 and 1995 do not report this species (reviewed by Van Damme et al. 2011a). However, *A.* cf. *gigas* was already a common species in the northern Bolivian Amazon by 2004 (Farell and Azurduy 2006). Its upstream advance in adjacent Bolivian watersheds appears to be continuing at a steady pace, being now present in the upper Beni River basin 20 km below Rurrenabaque (Miranda-Chumacero et al. 2012) (Figure 1). Its further expansion to the Mamoré river basin seems to have been blocked by rapids located in this river close to the Yata River mouth and the town of Guayaramerín (Carvajal-Vallejos et al. 2011) (Figure 1). Recent reports of *A.* cf. *gigas* in fish markets in the Iténez and Mamoré river basins (Doria and Souza 2012) can be traced to individuals that originate from the Beni River basin. However, Carvajal-Vallejos et al. (2011) mention that the presence of the species in these two river basins is to be expected, giving the uncontrolled trade and the introduction of juvenile fish by Bolivian aquaculture activities across the region.

In this paper, we describe the current distribution of *A.* cf *gigas*, as deduced from citizen reports and formal fisheries statistics, and explore the evolving impact of the species on the catch composition of fisheries in the Bolivian Amazon. We also seek to explain the invasion success of the species, as well as discuss the factors that might limit further expansion in the area. In doing so, we highlight gaps in knowledge about the invasion potential and ecological negative impacts of *A.* cf. *gigas* in new waters.

## Methods

Bolivia dismantled its formal public system of fish landing data collection in 1995 resulting in no governmental fish landing records being available for almost the last 20 years. This poses a formidable challenge for documentation of fisheries status or detection of trends in fish population numbers and distribution. To overcome this limitation, we employed two complementary approaches to assess the effect of *A.* cf. *gigas* introduction on fish landings in the Bolivian Amazon. The first approach is based on interviewing key informants in some of the main landing sites in the Amazon region in the year 2008, and the second approach is based on a period of intensive monitoring of fish landings in Riberalta, the principal fishing port in the Bolivian Amazon, during 30 consecutive days in May 2009. Local names of fish species are provided in Appendix 1.

*Interviews* - Interviews were carried out in the main landing sites in the northern Amazon in 2008, including Riberalta, Cachuela Esperanza and Villa Bella on the lower Beni River, Guayaramerín on the lower Mamoré River, Porvenir and Puerto Rico on the Orthon River, El Sena on the Madre de Dios River, and Rurrenabaque on the upper Beni River (Figure 1). These sites represent approximately 34% of all the commercial fishermen recorded in the Bolivian Amazon (Van Damme et al. 2011b). Key informants were identified through prior knowledge of the community, and were asked to estimate fish landings for the previous year (2007) of the most common native species and of *A.* cf. *gigas*. For the eight landing sites, a total of 19 key informants were interviewed, allowing the estimation of total annual landings for each location, as well as the estimation of relative catch composition. Interviews were conducted by the Bolivian research team, following informed consent protocols, as required by Bolivian standards. Data reported for each landing site, representing consensus data across the interviewees, were also informed by local fisheries data, commercial registers and reports by naval crew. According to the last population census conducted by the National Institute of Statistics (INE 2001), 84% of the commercial fishermen in paiche-area operated in Riberalta, Cachuela Esperanza, Villa Bella, Puerto Rico, Porvenir and El Sena. This figure was used to estimate total *A.* cf. *gigas* landings in this area.

*Fisheries landings* - Fisheries landings were recorded by an observer reporting catches in all the landing sites of Riberalta during May 2009. In total, landings by 50 commercial fishermen were recorded over a period of 30 days. Each fisherman provided detailed information on catch size, composition, fishing locations and fishing effort, with the observer checking catch and fish identity for accuracy. For the purpose of the present paper, origin of fish catch was assigned to the Beni, Madre de Dios and Orthon Rivers. These catch records represent an estimated 80% of the total catch for these landing sites, based on the number of active fishing boats in the area during the survey period. Basic economic data were also collected. On the basis of market prices for the different species recorded in the area, total market values of each species were calculated and the relative contribution of *A.* cf. *gigas* to gross income was estimated. According to regulations by the Ministry of Environment and Water, animal ethics approval is not required for the process of obtaining fisheries statistics.

*Data analysis* - Spatial patterns in *A.* cf. *gigas* landings were summarized using geographic mapping and measures of central tendency and variability. We examined the question of whether relative landings of *A.* cf. *gigas* were related to the distance to the point of initial invasion (Madre de Dios River) or, alternatively, to the surface area of permanent water bodies in each basin estimated from a spatial model developed by Crespo and Van Damme (2011). Moreover, approximate catch composition in the study area was used to estimate the production potential of *A.* cf. *gigas* in other Bolivian Amazon watersheds. This extrapolation was based on hydrographic and inundation maps published by Crespo and Van Damme (2011) and calculations of surface areas of different types of aquatic habitat presented by the same authors. Invasion rate was calculated by dividing the total distance between the escape point in Peru and the three first observation points in Bolivia (Carvajal-Vallejos et al. 2011) by the number of years between escape and first observation. Based on this estimated invasion rate, we estimated the time it would take *A.* cf. *gigas* to invade the Mamoré and Iténez basins along the main rivers stems starting from the locality of Guayaramerín in the lower Mamoré basin.

Cold temperature was considered as a potential factor that could control further expansion of *A. gigas* (Arantes et al. 2010). Water temperature data are scarcer and more difficult to obtain compared to air temperatures; therefore, it is common to use air temperature as a surrogate for water temperature in biological and water quality studies of streams (Rahel and Olden 2008). An air temperature map showing isotherms was elaborated based on 21-years of data (1990–2010) available from 20 SENAMHI monitoring stations (Appendix 2). The isotherms were drawn averaging the mean temperatures of the four sequential coldest days each year. Previous studies have linked warm-water species distributions to winter air temperatures (e.g., Bennett et al. 1997; Cortemedlia and Beitinger 2006). Information on *A.* cf. *gigas* mortality in natural waters and in fish culture stations was gathered through interviews and was plotted on the air temperature map. Telephone interviews were carried out of 12 aquaculture units and eight fisheries organizations in Riberalta, Porvenir, Puerto Rico, El Sena, Rosario del Yata, Trinidad, Puerto Villarroel, Santa Cruz and Rurrenabaque, to detect places where paiche mortality was observed during the last cold shock reported (July 2010). During this cold shock a high number of native fish died, mainly in the southeastern part of the Bolivian Amazon (Grande, Piraí and Ichilo rivers) (Petherick 2010; Van Damme et al. 2011c).

## Results

*Interviews* - Key informants reported the presence of at least 26 fish species in the 2007 catches (Appendix 3). Some local names may have been used in reference to more than one species, for example, within the genus *Mylossoma* and *Metynnis*, and family Curimatidae (Characiformes). Assuming that within these taxa only one species occurred, the contribution of the number of species of the orders Characiformes, Siluriformes, Osteoglossiformes and Perciformes to estimated catch composition would be 13, 10, 1 and 2, respectively (Appendix 3). *Arapaima* cf. *gigas* was the only non-native species reported in the catches.

Landings in Rurrenabaque (upper Beni River) and Guayaramerín (lower Mamoré River) were composed entirely of native species, with *A.* cf. *gigas* entirely absent from these sites (Figure 1). *Arapaima* cf *gigas* was recorded in the reported catches of Riberalta, El Sena, Puerto Rico and Porvenir, whose fishing areas largely overlap with the Madre de Dios, Yata and Orthon River basins, and with the middle and lower stretches of the Beni River. In Cachuela Esperanza and Villa Bella (lower Beni River), the species was rare (1% of total catch) and absent, respectively. In both localities, where fishing occurs in the rapids, migrating characids dominated the landings.

The key informants estimated a total catch of 784 t in the eight landing sites over a one-year period. Dominant orders were catfishes (Siluriformes) and characids (Characiformes), representing 36 and 34 % of the total catch. Native species or species groups contributing more than 10% to the total catch were *Colossoma macropomum* (Cuvier 1816), *Brycon* sp. (Characiformes), *Pseudoplatystoma* spp. and *Zungaro zungaro* (Humboldt 1821) (Siluriformes) (Appendix 3). *A.* cf. *gigas* contributed 29 % to total catch in the overall study area, equivalent to 225 t. Within the distribution area of *A.* cf. *gigas* published by Carvajal-Vallejos et al. (2011), total estimated catches of this species differed between landing sites. The highest catch was reported for Riberalta (179 t), whereas the localities with highest relative percentage of this species were Riberalta (49%), Porvenir (58%) and Puerto Rico (49%).

*Fisheries landings* - The monitoring of landings in Riberalta in May 2009 corroborated the findings from the interviews. A total catch of 12 t was recorded over a one-month period, 57 % of the catch originating from the Madre de Dios watershed, whereas 36 and 6% respectively originated from the Beni and Orthon watersheds. *A.* cf. *gigas* constituted 56% of the overall catch, whereas species of the orders Characiformes, Siluriformes, and Perciformes constituted 24, 18 and 1%, respectively (Appendix 4). The number of species in the Beni catch (28) was higher than in the Madre de Dios and Orthon watersheds, 14 and 2 species respectively. Moreover, *A.* cf. *gigas* was the most abundant species in the catch in the Madre de Dios watershed (74.2%), but less so in regions more distant from the point of invasion, such as the Orthon (52.7%) and Beni (28.5%) watersheds, notwithstanding the high surface area of lakes in the latter (Table 1).

The total market value of fish landings in Riberalta in May 2009 was 172 574 Bs (26 600 US$). *A.* cf. *gigas*, sold at an intermediate price in the markets (2 US$/kg) (Appendix 4), contributed 54% to this overall total. The remaining market value is attributed to large Siluriformes (25%) and Characiformes (21%).

*Distribution and estimated landings* – *A.* cf. *gigas* now occupies an estimated 24% of the floodplain lake surface in the Bolivian Amazon below 300 m above sea level. Estimated yield of *A.* cf. *gigas*, calculated on the basis of production data for 2007 and on surface area of floodplain lakes within the known Bolivian range of paiche, is equivalent to 0.76 kg/ha/year. An extrapolation of estimated current *A.* cf. *gigas* landings in its distribution area (258 t/year) to the rest of the Bolivian Amazon (< 300 m above sea level), yields an additional potential of 824 t/year.

The invasion speed of *A.* cf. *gigas* between the escape point in Peru and first record locations in Bolivia was estimated at 20.9 km/year (Table 2). If *A.* cf. *gigas* would start to invade the Mamoré and Iténez River basins starting in Guayaramerín (Figure 1), and assuming it invades at the same speed as demonstrated during its movement along the Madre de Dios River stem between Puerto Maldonado (where they were released) and the uppermost point in the Beni River, it would take 60 and 63 years respectively to reach the headwaters of the two river systems (at 280 m above sea level).

The current *A.* cf. *gigas* distribution is almost entirely bounded by the minimal temperature isotherms 11 and 12.5°C (Figure 2). This cold-water temperature limit is three degrees higher than in the southeastern Bolivian Amazon (8.5 – 9°C)

**Table 1.** Surface area of floodplain lakes and main river channel in the Madre de Dios, Beni and Orthon River basins, within the fishing area of Riberalta.

| | Madre de Dios | Orthon | Beni | Total |
|---|---|---|---|---|
| Surface area of lakes (km$^2$) | 59 | 15 | 78 | 152 |
| Surface area of rivers (km$^2$) | 257 | 147 | 219 | 623 |
| Surface area of lakes (%) | 19 | 9 | 26 | 20 |
| Total catch (kg) | 6 798 | 700 | 4 250 | 11 748 |
| % *A.* cf. *gigas* in the landings | 74 | 53 | 29 | |

**Table 2.** Invasion rate of *A.* cf. *gigas* between year of escape in Puerto Maldonado (1965) and first observation in three localities in the Bolivian Amazon. See map (Figure 1) for points of first record.

| Point of first observation | Coordinates | | Distance to Puerto Maldonado (km) | Year of first observation | Nr. of years between escape and first observation | Distance (km)/year |
|---|---|---|---|---|---|---|
| | X | Y | | | | |
| 1 | -66.5716 | -11.0997 | 290 | 1979 | 14 | 20.7 |
| 2 | -66.2331 | -10.9483 | 385 | 1983 | 18 | 21.4 |
| 3 | -66.9366 | -13.0478 | 880 | 2008 | 43 | 20.5 |
| | | | | | Mean: | 20.9 |

where highest rates of native fish mortality occurred in July 2010, due to cold-temperature shock, according to Petherick (2010). In this same area (Santa Cruz, Trinidad), all *A.* cf. *gigas* which were kept in two artificial ponds less than 1.5 m depth died, and mortality of the same species occurred in natural habitats close to Rurrenabaque (Figure 2).

## Discussion

Logistic challenges associated with comprehensive field surveys have prevented definitive studies on population sizes, distribution, and natural history of the invasive *A.* cf. *gigas* in Bolivia. Our study demonstrates the value of combining local citizen knowledge and fisheries landings data to understand the natural history and the invasion route of this introduced species, as well as its growing impact on local and regional economies.

The present study shows that in the Bolivian Amazon the species has transformed itself into a particularly successful piscivorous invader. This success can be partly explained by its equilibrium life-history strategy (sensu Winemiller 2005), in which low fecundity (Sánchez 1960; Greenwood and Wilson 1998), parental care (Sánchez 1960; Queiroz 2000) and delayed maturation (Lüling 1964; Ruffino and Isaac 1995) are favoured in relatively stable environments. For an air-breathing fish such as *A.* cf. *gigas*, the Bolivian Amazon presents floodplains with innumerous oxbow lakes, which are potential suitable habitat, despite periodic anoxic events and occasional cold water temperatures. Arantes et al. (2010) and Castello et al. (2011) showed that the species undertakes lateral migrations which allow it to explore, and eventually colonize, new floodplain lakes and adjacent slow-flowing rivers. This set of behavioural characteristics appears to have allowed the species to colonize the Bolivian Amazon, advancing at approximately 20 km each year.

Once settled in Bolivian waters, the species has become of high economic importance to a newly-created artisanal fishery. The available data suggest that it currently occupies a dominant position in the fishery. In a single decade, the *A.* cf. *gigas* fishery increased from being insignificant to one of the most important. Whereas the fish were entirely absent in the catches until 2000, it dominates the 2007 and 2009 landing estimations and data. Its prevalence in commercial fisheries may still grow, since there are some indications that in watersheds further away from the introduction point, the fisheries potential has not been reached yet (Table 1). This very fast growth of the fishery may reflect the high invasion potential of the species, likely also a consequence of the recent recognition of the commercial value of the species by fishermen, improved fishing practices, and development of local markets.

Whereas the species is growing in importance in Bolivia, it is considered vulnerable to extinction in most of its historical distribution range in the central Amazon, and is prone to overfishing (Castello et al. 2015). This may be reason to conclude that the exploitation pressure in the Bolivian Amazon is still low, as suggested by

Van Damme et al. (2011a), or that the methods used to capture this particular species in this area are not very efficient, as suggested by Miranda-Chumacero et al. (2012). Some socio-cultural factors may also explain landing patterns and overall low fishery pressure. The control over lake resources, including *A.* cf. *gigas*, lies mostly with indigenous people, who possess formal or informal exploitation (or protection) rights but do not participate very widely in *A.* cf. *gigas* fisheries. Since the Beni River basin includes more indigenous territory than the Madre de Dios and Orthon River basins, this could partly explain its relatively lower *A.* cf. *gigas* landings.

Based on our semi-quantitative estimates, current *A.* cf. *gigas* production is in the range of 0.76 kg/ha/year, assuming a surface area of 340 $km^2$ of floodplain lakes in the introduced range. This estimate is well above sustainable yields of 0.3 kg/ha/year reported for lakes in the Peruvian Amazon (Sánchez 1960) but below recommended yields of ~ 1.5 kg/ha/year based on a population model by Castello et al. (2011). However, our calculation did not account for streams and smaller tributaries, and these may also harbour exploited *A.* cf. *gigas* populations (Coca Méndez et al. 2012). On the other hand, tectonic lakes were not taken into account because it is not known whether they have been colonized by *A.* cf. *gigas*. Over-exploitation in the short term is likely improbable because access to many floodplain lakes is difficult or being controlled by indigenous people, who so far show little interest in commercial exploitation of the species.

*A.* cf. *gigas* appears to be a very successful invader. However, natural barriers may limit its further expansion in the Bolivian Amazon. Two factors are of particular importance to consider. The first one is the set of large rapids and waterfalls, which seem to be efficient barriers for migration of this species (Torrente-Vilara et al. 2011). Whereas downstream movement in the Beni river basin is probably not limiting for the species and would allow dispersion to the confluence of the Beni and Mamoré rivers, upstream movement in the Mamoré and Iténez watersheds may be precluded by a series of rapids in the lower stretch of the Mamoré river near Guayaramerín (Figure 1). How-ever, such barriers may be breached by occasional extreme floods, as experienced in early 2014.

Water temperature may also limit further expansion. Previous studies have linked warm-water species distributions to minimum temperature thresholds (e.g., Bennett et al. 1997; Cortemedlia and Beitinger 2006), and such models may serve to predict future distributions (Rahel and Olden 2008). In the study region, water temperatures can drop markedly with cold winds from the south during the winter. For example, a cold period in 2010 resulted in water temperatures as low as 4°C and was responsible for a massive fish kill in the central and eastern Bolivian Amazon (Petherick 2010). *A.* cf. *gigas*, whose natural distribution is in warmer areas of 24–30°C (Carvajal-Vallejos et al. 2011), may be intolerant to these cold water temperatures. The map of isotherms of minimum air temperatures (Figure 2) does not reflect such extreme events, but shows that the central and eastern parts of the basin are approximately 4°C colder than the northwest, which may constitute a natural barrier to the extent of invasion in natural waterbodies and its use in aquaculture.

Despite the size of the fish, and its reported role as a top predator, fisheries information is not conclusive on a possible negative impact on other commercial species (but see Miranda-Chumacero et al. 2013). However, support for this hypothesis is confounded by changes in targets by the commercial fleet as they shift from a more multi-species catch of migratory catfish species (predominantly *Pseudoplatystoma* spp.) and characid species (*C. macropomum, Piaractus brachypomus* (Cuvier, 1818)) to a more specialized fishing of *A.* cf. *gigas*. Some indigenous communities report that the paiche is reducing their catches of small characids, and, since *A.* cf. *gigas* is not traditionally utilized, see it as a pest that needs to be eliminated. On the other hand, development of the *A.* cf. *gigas* fishery could provide increased income and stability to rural and urban fishing livelihoods in a region of the country that is high in poverty and food insecurity. Sustainability of this endeavor depends on assessments of how much fishing pressure is offset by the invasive nature of *A.* cf. *gigas* in Bolivian waters, and implementation of management plans that take this into account. Proposals to actively introduce the fish to other Bolivian river basins that the fish has not yet reached, or to culture it in these watersheds, likewise need to be carefully evaluated to balance short-term vs. long-term benefits.

Our study demonstrates a considerable time lag (approx. 60 years) between initial introduction in southern Peru, and noticeable establishment and subsequent proliferation in the Bolivian Amazon. This same phenomenon was reported for exotic or extralimital species in Brazilian and

African rivers systems (Vitule 2009; Ellender and Weyl 2014) and is reason enough to consider the precautionary principle when contemplating planning of further introductions in sensitive aquatic ecosystems such as, for example, the Iténez river basin (Van Damme et al. 2013). Policy decisions on fishery and aquaculture activities will be important in determining the future of *A.* cf. *gigas* in Bolivia, and whether it should be viewed as a favorable new species or unfavorable invader. In this sense, the *A.* cf. *gigas* introduction in the Bolivian Amazon is an exemplary case which might inform us on the possible positive and negative impacts of future introductions which are likely due to continued aquaculture and dam development in the region.

## Acknowledgements

We thank fisheries organizations and aquaculture farms for support during interviews and field monitoring. We would like to thank especially Selín Trujillo (FEUPECOPINAB) and Gonzalo Serrate (CAOR). SENAMHI-Bolivia is acknowledged for providing temperature data. Paula Pacheco was particularly helpful in providing climatic data. This study was carried out with the aid of a grant from the International Development Research Center (IDRC), Ottawa, Canada (http://www.idrc.ca), and with financial support from the Government of Canada, provided through Foreign Affairs, Trade and Development Canada (DFATD) (www.international.gc.ca), in the framework of CIFSRF (Canadian International Food Security Research Fund), through the projects "Food Security, Fisheries and Aquaculture in the Bolivian Amazon" and "Amazon Fish for Food: Enhancing the pathways to poverty reduction and food security for women and indigenous families in Bolivia". The effect of cold temperature shocks on paiche was studied through the project "Base line for the integrated use of paiche (*Arapaima gigas*) in the north of the Beni province", supported by INIAF (Instituto Nacional de Innovación Agropecuaria y Forestal). JDO was supported by the University of Washington (School of Aquatic and Fishery Sciences) H. Mason Keeler Endowed Professorship. We thank Jean Vitule and an anonymous reviewer for providing useful suggestions that improved the manuscript.

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**Supplementary material**

The following supplementary material is available for this article:

**Appendix 1.** Local names of fish species recorded in commercial fish landings in the northern Amazon of Bolivia in 2008 (key informant interviews in eight landing sites) and 2009 (observer records in Riberalta).

**Appendix 2.** Climate data used for the development of the minimum air temperature map based on data available for the period 1990–2010.

**Appendix 3.** Species and catch volume (kg) in eight landing sites in the northern Bolivian Amazon in 2007 based on interviews with key persons.

**Appendix 4.** Species, catch volume (kg) and fish market prices in Riberalta in May 2009.

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