

Original article

Upstream dam impacts on gilded catfish *Brachyplatystoma rousseauxii* (Siluriformes: Pimelodidae) in the Bolivian Amazon

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This paper explores the effects of two run-of-river dams (Jirau and Santo Antônio) built in cascade in the middle Madeira River (Brazil) on the interruption of long-distance migration routes of the gilded catfish (*Brachyplatystoma rousseauxii*). A participative monitoring system was set up to compare capture by commercial fishers approximately 1500 km upstream of the dams in Bolivia, before (1998–2007) and after (2015–2017) dam closure. A significant decrease in gilded catfish catches and in catch per unit effort was observed after dam closure, whereas no significant difference in mean weight was found. Back-estimation of age suggests that the few individuals remaining after dam closure in 2009 are a mixture of old homers that returned upstream before dam closure, and residents hatched after dam closure and trapped in the upper Madeira. Unless fishways in the Madeira River dams improve their efficiency, the gilded catfish might become rare and in danger of regional extinction in the upper Madeira basin in the next few years, negatively affecting river fisheries.

Keywords: Environmental impact, Fish migration, Fishways, Madeira dams, River connectivity.

Este estudio explora el impacto de las represas en cascada Jirau y Santo Antônio en el curso medio del río Madeira (Brasil) sobre la interrupción de la ruta de migración del bagre dorado (*Brachyplatystoma rousseauxii*). Se estableció un sistema de monitoreo participativo para comparar la captura de dorado por pescadores comerciales en Bolivia, aproximadamente 1 500 km río arriba de las represas, antes (1998–2007) y después (2015–2017) de su cierre. Se observó una disminución significativa en las capturas y en la captura por unidad de esfuerzo de dorado después del cierre de ambas represas. No hubo diferencias significativas en el peso promedio antes y después del cierre. La estimación de la edad de los pocos individuos capturados arriba de las represas sugiere que se trata de una mezcla de individuos adultos que han podido pasar las represas antes de su cierre en 2009, y residentes nacidos después del cierre de las represas, atrapados en el alto Madeira. Si los sistemas de traspaso de peces implementados en las represas del río Madeira no mejoran su eficiencia, el dorado podría volverse escaso y en peligro de extinción regional en la cuenca alta del Madeira en los próximos años, afectando negativamente la pesca de esta especie.

Palabras clave: Conectividad de ríos, Impacto ambiental, Migración de peces, Represas del río Madeira, Sistemas de traspaso de peces.

Introduction

Dams are considered one of the main pressures leading to aquatic habitat degradation in the Amazon river basin (Winemiller *et al.*, 2016; Castello, Macedo, 2016; Lees *et al.*, 2016; Forsberg *et al.*, 2017; Latrubesse *et al.*,

2017; Timpe, Kaplan, 2017). The planned construction of hydroelectric dams along the Andes-to-Amazon gradient and the creation of reservoirs will increasingly interrupt free water and sediment flow (Anderson *et al.*, 2018). One of the most cited impacts of these dams is on long-distance migratory fish species, the completion of their life cycle

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depending on river connectivity (Anderson *et al.*, 2018), preservation of the hydrological cycle (Lima *et al.*, 2017) and the availability of suitable upstream spawning habitats (Barthem *et al.*, 2017). These impacts on migratory fish are difficult to mitigate, although there is past and ongoing research and experimentation on fishways performance (Godinho, Kynard, 2009; Baigún *et al.*, 2012). Given the low efficiency of these systems for Neotropical species (Oldani *et al.*, 2007; Baigún *et al.*, 2007; Pompeu *et al.*, 2012; Lira *et al.*, 2017), in some cases aquaculture has been proposed as mitigation strategy, even though this activity may affect fisheries resources indirectly (see, for example, Pelicice *et al.*, 2014; Montanhini Neto *et al.*, 2015).

Two run-of-river dams (Jirau, Santo Antônio) have been constructed in cascade in the middle Madeira River, in Brazil, downstream of the Bolivian-Brazilian border. The impacts of this type of dams on the aquatic environment is due to changes in hydrological and sediment regimes, and position along fish migration routes (Fearnside, 2014; Santos *et al.*, 2018), affecting especially migratory catfish (Duponchelle *et al.*, 2016; Hauser, 2018; Hauser *et al.*, 2018; Hauser *et al.*, 2019) and fisheries (Lima *et al.*, 2017; Santos *et al.*, 2018). The latter authors reported a 74% reduction in fish landings downstream of the Madeira dams during construction and after closure (2009–2014).

The gilded catfish *Brachyplatystoma rousseauxii* (Castelnau, 1855) is the species most affected by these dams. This catfish undertakes the longest migrations known in freshwater habitats (Barthem, Goulding, 1997; Coronel *et al.*, 2004; Duponchelle *et al.*, 2016; Barthem *et al.*, 2017; Hauser, 2018) and spawns in Bolivia mainly in the upper Beni and Mamoré rivers, which are Amazonian headwaters close to the lower Andean foothills (Van Damme *et al.*, 2011; Barthem *et al.*, 2017). Larvae and juveniles drift downstream more than 4000 km and reach the Amazon estuary, where they feed during approximately two years, after which they disperse upstream across the basin, and undertake upstream migration to their spawning habitats (Barthem, Goulding, 1997; Barthem *et al.*, 2017). Duponchelle *et al.* (2016) and Hauser (2018), based on population studies and strontium isotope analysis of otoliths, provided evidence that for most individuals in the Madeira basin natal homing is the normal behavior to complete their life cycle, although a low percentage of the individuals encountered in the Bolivian Amazon were natural residents with unknown reproduction pattern. Most gilded catfish that migrated upstream and passed the waterfalls in the Bolivia-Brazil border area in the pre-dam period (now partly flooded by dams) stayed in the upper Madeira (Bolivian and Peruvian territory) afterwards and never returned to the lower Madeira or Amazon (Duponchelle *et al.*, 2016; Hauser, 2018). Annual spawning of these individuals in the headwaters is suggested by the presence of ripe individuals between February and April (Coronel *et al.*, 2004) and by the increased abundance of downstream drifting larvae and juveniles in the dry season in survey sites close to the dams (Cella-Ribeiro *et al.*, 2015).

Duponchelle *et al.* (2016) and Hauser (2018) showed that the typical homing behavior of gilded catfish is now interrupted due to the Jirau and Santo Antônio dams restricting passage of upstream migrating pre-adult gilded catfish. However, the potential impacts of these dams in the upper Madeira basin in Bolivian territory have not yet been assessed (MRE-MMAyA, 2014). Appraisal of these impacts on migratory fish in the upper Madeira was so far hampered by the fact that Environmental Impact Studies or Assessments were limited to the area in Brazilian territory immediately adjacent to the dams, with effects upstream of the Brazilian-Bolivian border being underestimated.

The objective of this study was to assess the impact of the closure of the Jirau and Santo Antônio dams on the gilded catfish population in the upper Madeira River basin, using fishery landing data. We first assessed whether there existed a negative population trend in the pre-dam period caused by either natural or anthropogenic factors other than dams, and which eventually might explain population decrease in the post-dam period. We then investigated the hypothesis that dams affected gilded catfish by comparing pre-dam and post-dam catch, catch per unit effort (CPUE), fish weight and age. The probability of dam-induced regional extinction of the species was discussed interpreting both published literature and observed changes in fish landings.

Material and Methods

Study area. The study was conducted in the Ichilo River, an Amazon headwater of the Mamoré River, tributary of the Madeira River. The main landing site in the study area is Puerto Villarroel, a small town of 3000 habitants in Bolivia, where navigation, commercial fishing and tourism are the main activities providing family income and employment (Van Damme *et al.*, 2011) (Fig. 1).

The river originates upstream of the Carrasco and Amoró National Parks (Bolivia) at an altitude of 4500 m above sea level. The climate is humid to hyperhumid, with annual rainfall of 2 497 mm and mean annual temperature of 23.6°C (Navarro, Maldonado, 2002). The river stretch used by commercial fishers has a length of approximately 300 km and an altitude between 160 and 190 m above sea level. Fisheries resources are exploited in the main river channel, in small tributaries and in oxbow lakes. The river exhibits two well defined hydrological peaks characterized by highest water levels in summer (February – March) and lowest water levels at the end of the winter (August – September).

Santo Antônio and Jirau dams, located in the Madeira River (Brazil), were constructed in different stages between 2008 and 2016 (Santos *et al.*, 2018). The construction of the Santo Antônio dam (08°48'S 63°56'W), situated 1768 km downstream of Puerto Villarroel and 100 km downstream of Jirau dam (Fig. 1), started in September 2008. Reservoir filling started in September 2011, when the first of the sluice gates was closed. The first turbines began to operate on March 30th 2012, and all 50 turbines were operational in

November 2016. This dam possesses a fishway composed of an artificial channel foreseen with a river-type substrate and simulating the original Madeira River flows in the rapids (Fearnside, 2014). Jirau dam construction started in June 2009, the river was dammed to fill the reservoir in October 2012, the first turbine began operating in September 2013 and the construction was completed in December 2016 with 50 turbines. The fishways of this dam consist of two artificial channels equipped with a fish attraction system and a tank, where the fish are trapped, manually selected and subsequently transferred upstream by a truck.

Methods. A participative monitoring system of catches was set up with fishers of Puerto Villarroel, with data collected from an average annual number of 9.9 (± 3.9 ; range 4–17) commercial fishery boats participating between 1998 and 2007 (10 years pre-dam period) and 8.7 boats (± 2.5 ; range 6–11) between 2015 and 2017 (three years post-dam period). This number of boats is equivalent to approximately 80% of the total fishery fleet in Puerto Villarroel (Van Damme *et al.*, 2011). Data for the period 2008–2014 were not available. Overall, captured fish were monitored daily on board during 768 fishing trips over the 13-year monitoring period, 666 before and 102 after dam closure. A form filled by trained fishers during each trip provided daily catch data by species, individual fish weight, as well as information on fishing gear, fishing location and crew members. Such form generally covered fishing trips of between 4 and 20 days with a crew of two to four fishers.

Gilded catfish is captured in the Ichilo River channel, where it forms part of a multi-species catfish fisheries (Doria *et al.*, 2018a). We calculated river catch as the sum of catfish species caught in rivers using five fishing methods: hooks fixed to drifting boys (locally denominated as “bidónes”), fixed hooks on lines (“espineles”), longlines, drifting gill nets with large mesh size and enclosure nets used in shallow waters along the shore line. Catch using drifting nets with small mesh size, used in the capture of *Prochilodus nigricans*, and the catch of the scavenger species *Calophysus macropterus* using bait immersed in submerged cages were excluded from the analysis. Driftnets also occasionally capture a large frugivorous characid belonging to the order Characiformes, *Colossoma macropomum* (named “pacú” in Bolivia).

Individual gilded catfish weights estimated by fishers were obtained from 459 individuals, 445 before and 14 after dam closure. Fishers were trained in estimating individual weights at the beginning of each sampling period, in 1998 and 2015 respectively, by using a scale with a capacity of 50 kg, and thereafter all weights of captured catfish were estimated visually by the fishers. Only 72% of the individual weights were included in the analysis because fishers grouped the weights of some individuals. No distinction was made between males and females. Specimens were deposited in the collection of the Unidad de Limnología y Recursos Acuáticos (Universidad Mayor de San Simón) in the Museo de Historia Natural Alcides d’Orbigny, Cochabamba, Bolivia (catalogue number UMSS 07208).

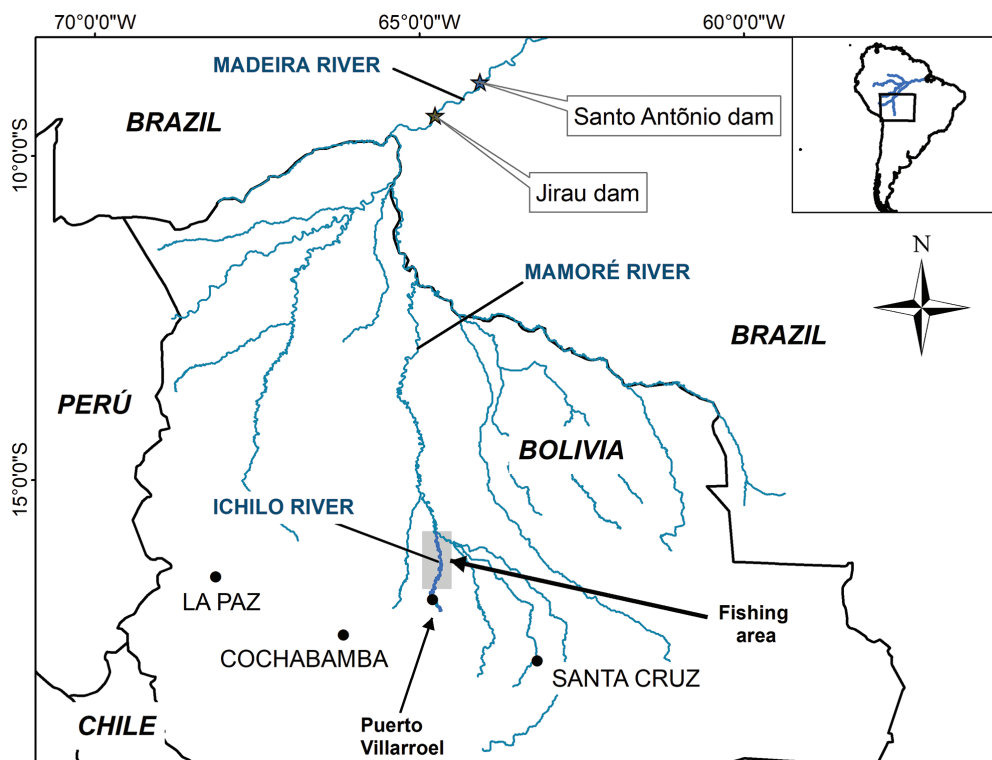


Fig. 1. Upper Madeira River basin, showing landing site Puerto Villarroel and fishing area in the Ichilo River (Bolivian Amazon), as well as the Santo Antônio and Jirau dams (Brazilian Amazon).

Data Analysis. We calculated the monthly and annual contribution of gilded catfish to total river catch before and after dam closure. Catch per unit effort (CPUE) was calculated as the gilded catfish catch (in kg) by one fisher per day. Trends in gilded catfish CPUE between 1998 and 2007 were tested by linear regression analysis to evaluate whether there might have been a downward trend before dam closure, which eventually might explain the observed low CPUE after dam closure. Differences in percentage contribution of *B. rousseauxii* to catch and differences in CPUE before and after dam closure were tested by a non-parametric test (Kruskal-Wallis one-way ANOVA on ranks).

Kruskal-Wallis test was also used to evaluate weight differences between individuals before and after dam closure. Length and age range of the individuals caught by fishers before and after dam closure was back-estimated from weights using the standard length (SL) – weight (W) relationship $W = 0.02 \text{ SL}^{2.936}$ ($r^2=0.894$) and the von Bertalanffy growth equation $SL_t = 102.84 (1 - e^{-0.57(t - 0.021)})$, with $t = \text{age}$ (in years) (from Hauser *et al.*, 2018). Age variation for each weight class was used to explore the possible life cycle of individuals registered in the pre-dam and post-dam period. Based on Hauser *et al.* (2018), individuals captured in the upper Madeira basin weighing between 7–8 kg have an age between 2.5 and 5 years old, individuals of 9 kg have any age between 3 and 7 years old, whereas individuals > 9 kg could have any age between 3 and 15 years.

Results

Catches in the Ichilo River were characterized by long- and medium-distance migratory species. The nine larger catfish species (family Pimelodidae) caught were typical riverine species exhibiting various types of longitudinal and lateral migratory behavior (Tab. 1).

Total river catch registered in the pre-dam period was 243 tons, with an average of 24 (± 9) tons/year (N=10 years), whereas in the post-dam period the total was 49 tons (N=3 years), with an average of 16 (± 5) tons/year. The contribution of gilded catfish to total river catch decreased after river damming. Before dam closure, the species accounted for 5.5 (± 2.5) % (range 1.8-10.3%) of river catch, whereas it only accounted for 0.4% (± 0.1) (range 0.3-0.5%) after dam closure (Fig. 2). Before closure, annual CPUE of gilded catfish fluctuated between 0.34 and 1.56 kg/fisher*day, with a mean of 0.78 (± 0.39) (Fig. 2). There was no significant negative trend in the slope of the linear regression of catch per unit effort against time ($b=-0.025$; $F=0.326$, $p>0.05$) before dam closure. Annual CPUE levels of gilded catfish in the post-dam period were below 0.13 kg/fisher*day, which was a significant decrease in comparison with the pre-dam period (Kruskal Wallis, $H = 6.43$; $p = 0.01$).

Gilded catfish showed a very distinctive seasonal pattern in the study area, with mature individuals appearing in the catch in October or November, when water levels start to

rise, and reaching a peak during the receding water period from March to May (Fig. 3). Before dam closure, 70.4% of all gilded catfish were caught in March and April. In these months, average CPUEs were of 3.4 and 1.6 kg/fisher*day. The species almost disappeared from the catch during the low water period, notwithstanding the continued effort using catfish-specific fishing methods, to appear again at the beginning of the raining season in November–December when water level started increasing again. The low catch between December and February coincided with the observed low fishing effort during prohibition of commercial fishing by the government regulations. After dam closure, although catfish-specific effort throughout the receding and low water periods remained high, there was a significant drop in monthly CPUE, below 0.02 kg/fisher*day throughout the year (Fig 3).

The mean weight of the 445 individuals caught before dam closure was 9.4 (± 3.0) kg, ranging between 4 and 17 kg, whereas the mean weight of the 14 individuals caught after dam closure was 13.0 (± 3.7) kg, all weighing 7 kg or more (Fig. 4). Nevertheless, there was no significant difference in mean weight before and after dam closure (Kruskal Wallis; $H=3.19$; $p=0.07$). Of the 14 individuals captured after dam closure, one individual captured in 2016 and two individuals in 2017 weighed respectively 8 and 7 kg.

Tab. 1. Fish species caught in the Ichilo River recorded by fishers of Puerto Villarroel. Within each order species are listed in alphabetic order. M1=Long-distance longitudinal migration; M2=Intermediate distance longitudinal migration, ML=Intermediate distance longitudinal and lateral migration (following Barthem, Goulding, 2007).

Species name	Local names	Migratory habits
Order SILURIFORMES		
<i>Brachyplatystoma filamentosum</i> (Lichtenstein, 1819)	Bacalao	M2
<i>Brachyplatystoma rousseauxii</i> (Castelnau, 1855)	Dorado, plateado	M1
<i>Brachyplatystoma platynemum</i> Boulenger, 1898	Barbachata	M1
<i>Phractocephalus hemiliopterus</i> (Bloch & Schneider, 1801)	General	ML
<i>Pseudoplatystoma fasciatum</i> (Linnaeus, 1766)	Surubí	ML
<i>Pseudoplatystoma tigrinum</i> (Valenciennes, 1840)	Chuncuina	ML
<i>Oxydoras niger</i> (Valenciennes, 1821)	Boni	M2
<i>Sorubimichthys planiceps</i> (Spix & Agassiz, 1829)	Paleta	M2
<i>Zungaro zungaro</i> (Humboldt, 1821)	Muturo	M2
Order CHARACIFORMES		
<i>Colossoma macropomum</i> (Cuvier, 1816)	Pacú	ML

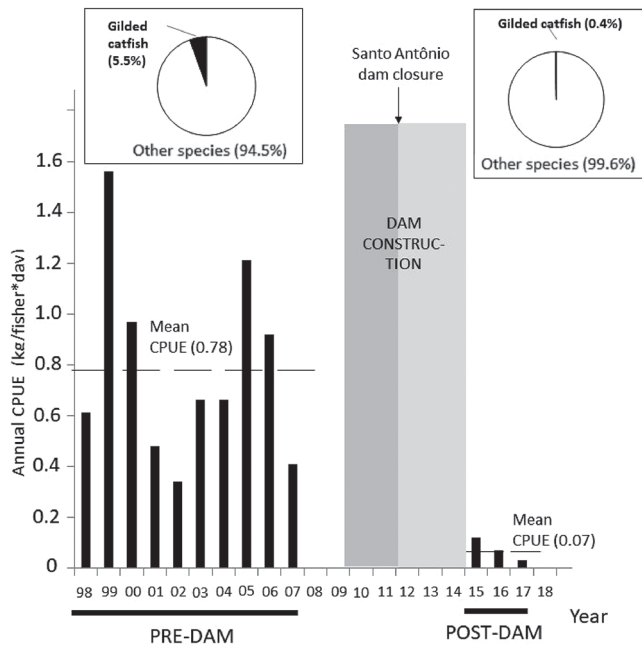


Fig. 2. Annual catch per unit effort (CPUE) of *Brachyplatystoma rousseauxii* before and after dam closure. The horizontal dotted line before dam closure depicts the mean annual CPUE between 1998 and 2007. The inserted diagrams show the relative contribution of gilded catfish to river catch before and after closure.

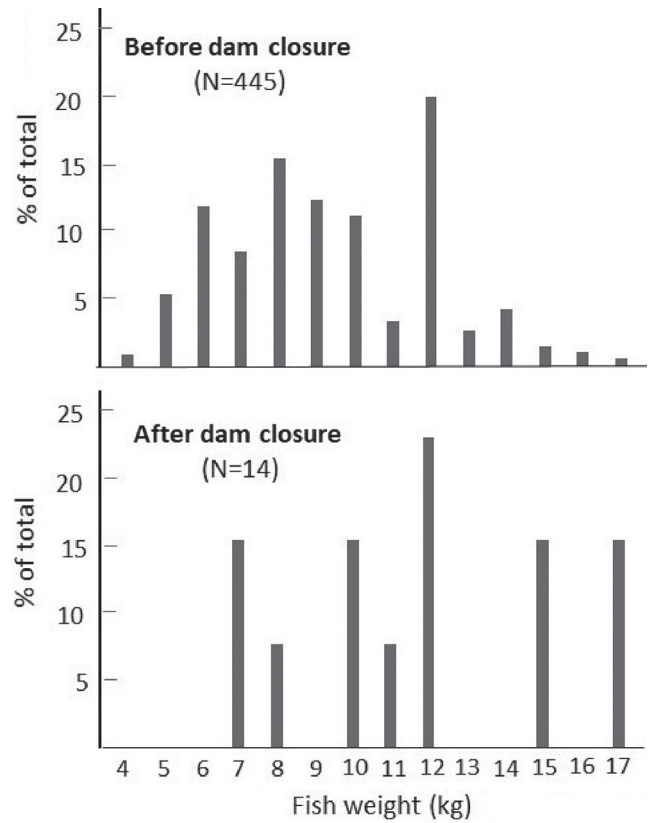


Fig. 4. Fish weight frequency distribution of *Brachyplatystoma rousseauxii* before and after dam closure.

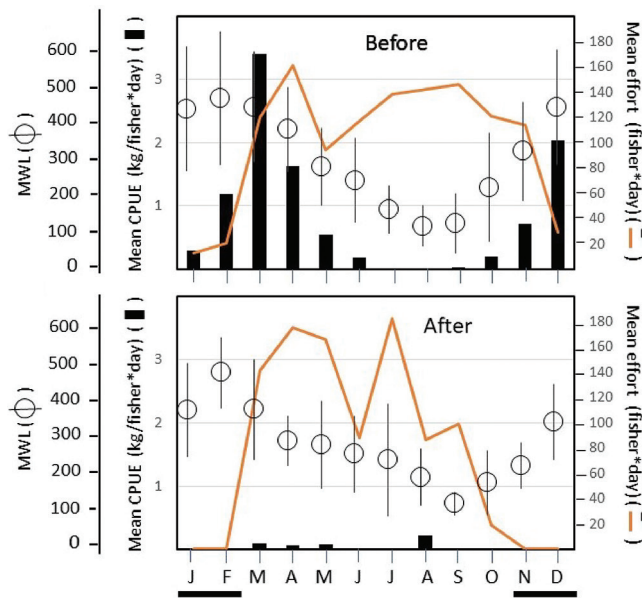


Fig. 3. Mean annual fishing effort and capture per unit effort (CPUE) of *Brachyplatystoma rousseauxii* (black bars) per month in the Ichilo River before (1998–2007) and after dam closure (2015–2017) using catfish-specific fishing methods. Mean monthly water level (MWL) in Puerto Villarroel for the two sample periods is shown (SENAMHI 2018), with vertical lines representing standard deviation. The horizontal bars show the period when commercial fishing is prohibited.

Back-estimation of age indicated that 42% of the individuals captured before dam closure weighed <9 kg and were thus 5 years or younger, and the remainder 58% were individuals weighing 9 kg or more, with ages between 3 and 15 years. After dam closure the three smallest individuals (7–8 kg), which could be between 2.5 and 5 years old, represented 21% of all individuals captured, and the remaining ones with weights >9 kg, which could have been anything between 3 and 15 years old, represented the remaining 79%.

Discussion

Commercial fisheries have been put forward in the past as one of the possible causes of gilded catfish population decline in the Amazon basin. However, although the species is intensively exploited along its upstream migration route in the Madeira and Lower Amazon rivers (Barthem, Fabr e, 2004; Barthem, Goulding, 2007; Batista *et al.*, 2012; Cruz *et al.*, 2017), no significant decrease in capture per unit effort was observed in the middle Madeira River in the decade before start of dam construction (Lima *et al.*, 2017; Doria *et al.*, 2018b). The present study equally showed no negative population trend before dam construction at sites upstream from the dams in the upper Madeira River basin. This suggests that the dams represent the main cause of post-dam gilded catfish population decline, the same as was reported by Lima *et al.* (2020) in the middle Madeira River.

The gilded catfish has a low natural abundance in the study area and occurs seasonally during the breeding season (Van Damme *et al.*, 2011), making it difficult to detect long-term population trends. Notwithstanding its overall rarity and seasonal occurrence, the species was captured annually in the Ichilo River during 10 consecutive years between 1998 and 2007 before dam closure, and these data provided a reliable base line for post-dam impact evaluation. Detection of gilded catfish population trends by means of CPUE in the present study, however, was hampered by differences in sampling efficiency before and after river damming. Particularly during high water conditions from November to February, the capture by commercial fishers could not be adequately monitored with the present methodology due to the annual fisheries ban promulgated yearly by the regional government, and corresponding drop in fishery effort. This ban was imposed more efficiently after dam closure, affecting the possibility to obtain comparable CPUE data especially during increasing and high-water levels. A reliable comparison could only be made for the months of receding waters (March–June).

Notwithstanding these limitations, the upstream monitoring of fish catches provides evidence that the Jirau and Santo Antônio dams have interrupted the former dominant migratory pattern of the gilded catfish, which involved a compulsory prolonged stay of immature fish in the estuary area (Duponchelle *et al.*, 2016). Both dams are provided with types of fishways, of which the fish passing efficiency has been questioned in repeated occasions (Agostinho *et al.*, 2008; Lira *et al.*, 2017), and it is now generally assumed that they will not allow for the successful upstream migration of pre-adult goliath catfishes (Fearnside, 2014; Hahn *et al.*, 2017; Cella-Ribeiro *et al.*, 2017). Hauser (2018), using otolith microchemistry, recently provided clear evidence that, although some downstream passage of larvae and juveniles of gilded catfish through fishways, turbines or spillways cannot be excluded, pre-adults migrating upstream cannot pass these structures. The rupture of recruitment of new individuals from downstream would mean that the individuals caught in the upstream Madeira after dam closure are mostly old homers which had passed before dam construction.

In the worst-case scenario, where the fishways would remain ineffective to accommodate the upstream passage and recruitment of new homing sub-adults, the remaining old reproducing homers will gradually disappear from the upper Madeira due to natural and fishing-induced mortality. This population decrease probably contributes to explaining the decreasing CPUE observed during the post-dam period. As the maximum observed age was 15 years in the Madeira River (Hauser *et al.*, 2018) and assuming that the last homers that returned to Bolivia were 3 to 4 years old in 2011 before dam closure (Hauser, 2018; Hauser *et al.*, 2018), they could become extinct in the upper Madeira basin approximately twelve years after Santo Antônio dam closure, hence around 2024.

Microchemistry analysis of otoliths (Hauser, 2018) has shown that since the dam's closure most of the old homers' offspring became "forced residents", being trapped upstream of the dams within the upper Madeira. However, the relative contribution of these fishes to the catch in the Ichilo River is still unclear, due to the difficulty of back-calculating individual age based on weight data. Weights and/or fish lengths are inherently weak predictors of age owing to the sigmoid nature of the weight- or length-age curve of the species (Hauser *et al.*, 2018). Based on weight data, the gilded catfish captured in the study area in the pre-dam period (1998–2007) might have had any age between 2–3 and 15 years old, their maximum observed age in the Madeira basin (Hauser *et al.*, 2018). Moreover, there is a significant size dimorphism between males and females in *B. rousseauxii* (García Vásquez *et al.*, 2009; Agudelo Córdoba *et al.*, 2013; Hauser *et al.*, 2018), additionally limiting the possibility of age prediction in the present study, entirely based on unsexed mature individuals. This means that based on weight data alone the relative contribution of old reproducing homers and forced residents to the catch cannot be established. In the post-dam period (2015–2017), most individuals caught had probably returned to the upper Madeira before dam closure, but the smallest fish (7 and 8 kg) probably are forced residents trapped above the dam, as they would be too young to have migrated back to the upper Madeira before dam closure (see Hauser, 2018).

The forced residents trapped upstream of the dams have a slower growth than homers (Hauser, 2018), which might further impact recruitment as fecundity is proportional to body length and weight (García Vásquez *et al.*, 2009). Alternatively, some of these residents might adapt to this reduced life cycle and hopefully rebuild a sustainable population in time, providing that eggs and larvae can find appropriate habitats, and that fishing and natural mortalities will not outweigh recruitment. However, the strong decline in number of *B. rousseauxii* in the upper Madeira after dam closure suggests that only very few forced residents survive to adulthood. To predict how resident individuals, both natural or forced, will be affected by the dams, key information is still missing on their reproductive capabilities. It will be necessary to analyze otoliths of ripe or just spent individuals using Sr isotopic analyses, in order to determine whether resident individuals actually do participate in reproduction.

The possible extinction or the strong reduction of *B. rousseauxii* in the Madeira basin would have both economic and ecological consequences at a regional scale. In Bolivia, the species contributed to approximately 5% of annual commercial fisheries landings (Van Damme *et al.*, 2011) and represents an actual economic value of more or less 56 000 US\$ (Navia *et al.*, 2019). Before dam closure (2004–2008) the gilded catfish commercialized in the Porto Velho fish market, which is the largest in the Brazilian portion of the Madeira basin, represented an economic value of

approximately 345 000 US\$ (Lima, 2017). Because it is an apex predator (Barthem, Goulding, 1997; Barbarino Duque, Winemiller, 2003; Angelini *et al.*, 2006), it is likely that its depletion would generate top-down cascading impacts on food webs (Angelini *et al.*, 2006; Duponchelle *et al.*, 2016; Lima *et al.*, 2020), with additional unpredictable socio-economic impacts. Also, since forced residents have a lower growth rate than specimens performing the complete migratory life cycle (Hauser, 2018) fishery quality could be affected even if the species could adapt to a shorter life cycle within the upper Madeira River, avoiding the lower Amazon as a growing area. It is also necessary to assess if the Madeira populations could use alternative spawning grounds in other Amazonian rivers. Hauser (2018) found that approximately 8% of the Madeira individuals were strayers hatched in the upper Amazon and hence not showing compulsory homing. Further ecosystem and economic modeling would be necessary to evaluate future scenarios at a basin scale.

We recommend that *B. rousseauxii* should by now be considered endangered in the Upper Madeira basin, having fallen to less than 10% of its base line CPUE, using criteria established by IUCN (2017). The presence of homing at basin-scale may enhance the extinction probability of the upper Madeira basin population and promote the disappearance of a complete genetic line and impoverishment of the overall genetic variability of the species (Carvajal-Vallejos *et al.*, 2014). Mitigation measures will be necessary to avoid the extinction of *B. rousseauxii* in the upper Madeira. As this species performs very long transboundary migratory movements, international management policies along the basin are needed. Also, efficiency at both fishways should be improved to ensure that gilded catfish preadults can pass upstream (Hauser, 2018) as well as to reduce the mortality rate triggered by the reservoir, turbines and spillways on larvae drifting downstream (Molina Carpio, 2011). As several more dams are planned for the basin (Winemiller *et al.*, 2016; Latrubesse *et al.*, 2017; Anderson *et al.*, 2018), impacts on large migratory catfish should be considered at a larger scale than traditional impact studies did (Goulding *et al.*, 2019).

This study documented for the first time how dams affected upstream populations of large catfish in the Amazon basin and impacted on artisanal fisheries sustainability. Although the Madeira case can be considered as a pioneer study case for whitewater rivers in the Amazon, it offers reliable evidence that river fragmentation could have a strong impact on large migratory catfishes, that cannot be mitigated or ameliorated by current fish passage technologies. The observed decline of the gilded catfish is a strong indication that populations of other long-range or mid-range migratory species might respond similarly to the dams. This situation will aggravate if the other planned dams on the Madeira basin or other Amazonian large rivers are to be implemented.

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