

LETTER

Quantitative impacts of hydroelectric dams on the trans-Amazonian migrations of goliath catfish

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Abstract

Hydropower expansion is increasingly responsible for connectivity and biodiversity loss in freshwater ecosystems. The Amazon basin, which supports the highest level of freshwater biodiversity globally, faces such unplanned expansion. Here, we demonstrate and quantify the impacts of two major hydroelectric dams on the Madeira River on the trans-Amazonian movements of one apex predatory catfish (*Brachyplatystoma rousseauxii*) performing the longest migration known in freshwaters. Using otolith microchemistry, we show that above the dams, the former basin-wide homing migration between the breeding grounds in the upper Madeira and the nursery in the Amazon estuary has now been replaced by residency. We found evidence suggesting downstream migration of juvenile fish past dams into the Amazon estuary and that some of them home back to the Madeira. However, we did not find evidence that the fish homing back from the estuary can access their breeding grounds in the upper Madeira; they remain blocked

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below the dams. Our results provide undisputable evidence that the conservation of the species primarily requires the reestablishment of connectivity with the construction of efficient fishways.

KEYWORDS

Brachyplatystoma, breeding area, estuary recruitment, landlocked population, Madeira River, natal homing, residency

1 | INTRODUCTION

The effects of overexploitation, flow modification, habitat degradation, climate change, and invasion by exotic species make freshwater biodiversity significantly more at risk than terrestrial or marine biodiversity (Leal et al., 2020; Reid et al., 2019). Hydropower development and its cortege of harmful impacts, especially the loss of connectivity, are arguably among the worst and most rapidly growing threats to the conservation of freshwater biodiversity (Barbarossa et al., 2020; Caldas et al., 2023; Winemiller et al., 2016; Zarri et al., 2022). The Amazon River and its tributaries, which represent the most speciose freshwater ecosystem in the world, face those major perturbations and conservation issues (Castello & Macedo, 2016; Castello et al., 2013; Latrubesse et al., 2017). The whole system is highly reliant upon hydrological connectivity (Castello et al., 2013) and still holds a large proportion of very long free-flowing rivers (Grill et al., 2019). Most, however, will have their connectivity severely impacted by planned hydropower infrastructure development (Barbarossa et al., 2020; Caldas et al., 2023; Castello & Macedo, 2016; Winemiller et al., 2016). Yet, the still relatively preserved river connectivity of the Amazon basin is considered of disproportionate global importance for the provision services it provides, including fisheries and food security to millions of people, sediment transport, and biodiversity conservation (Barbarossa et al., 2020; Castello & Macedo, 2016; McIntyre et al., 2016).

Since 1970, freshwater megafauna (animals with a body mass ≥ 30 kg) have globally declined by 88% and mega-fish by 94%, mainly owing to their large size, complex habitat requirements, and specific life histories (He et al., 2019), but also to direct human consumption (Ripple et al., 2019). Mega-fish performing extensive migrations, such as the Amazonian goliath catfishes (Pimelodids of the genus *Brachyplatystoma*; Barthem et al., 2017), are even more at risk as they rely on distant interconnected habitats whose connectivity can easily be interrupted by dams (Duponchelle et al., 2021; Pereira et al., 2023). Additionally, these species are of prime economic importance and support intensive fisheries throughout the Amazon basin,

particularly in the estuary region by industrial fisheries targeting juveniles (Barthem & Goulding, 2007). For example, the species *Brachyplatystoma rousseauxii* perform the longest known migration in freshwaters, up to 12,000 km, between their breeding grounds in the white-water tributaries of the upper Amazon and upper Madeira sub-basins and their nursery areas in the lower Amazon estuarine region (Barthem et al., 2017; Duponchelle et al., 2016; Figure 1). Using otolith (ear stones) microchemistry, it was shown that the exceptional life cycle of *B. rousseauxii* involves a natal homing behavior, whereby most individuals return to reproduce in the geographic area where they were hatched in the only two known breeding areas: the upper Madeira (Duponchelle et al., 2016) and the upper Amazon (Hauser et al., 2020). However, two large hydroelectric dams—Jirau and Santo Antônio—have been built in the Brazilian portion of the Madeira River in 2011 and 2012, respectively (Cella-Ribeiro et al., 2017), with considerable potential for disrupting the trans-Amazonian migration of this apex predator (Figure 1). Recent evidence indicates that after the dams' closure, the species' fisheries and captures have markedly declined within the upper Madeira (Van Damme et al., 2019), but also in the Brazilian portion of the Madeira, both above and below the dams (Cella-Ribeiro et al., 2017; Lima et al., 2020; Santos et al., 2018). A telemetry study further provided evidence that Santo Antônio's fishway (Jirau does not have one) is ineffective for the species and other goliath catfishes (Hahn et al., 2022). Yet, the actual effect of these two dams on the migration of *B. rousseauxii* remains a major knowledge gap in devising conservation actions. Here, using otolith microchemistry from samples collected in strategic locations before and after the dams' completion, we analyze and quantify the impacts of the dams on the migratory patterns of *B. rousseauxii* and propose conservation measures.

Specifically, we investigated the following research questions: what were the proportions of natal homers, natural residents, and strayers in the Madeira before the dams and what are they now, after the dams? Regarding the situation after the dams, are the fish hatched in the upper Madeira able to reach their former nursery grounds in the Amazon estuary, and if so, are these fish able to home back to their



FIGURE 1 Map of the Amazon basin with the main tributaries and their $^{87}\text{Sr}:^{86}\text{Sr}$ isotopic values, showing the main cities (yellow squares) and fish sampling stations (red squares). The two short black lines upstream of Porto Velho on the Madeira sub-basin indicate the approximate position of the two recently built hydroelectric dams: Santo Antônio Energy (downstream) and Jirau (upstream). The two crescent shape forms represent the two known breeding areas, in the upper Amazon (translucent blue) and upper Madeira (translucent red).

former breeding grounds in the upper Madeira? Lastly, as observed in other fish species (Gillanders et al., 2015), we investigated whether residency impacted the growth of individuals when compared with migratory ones.

2 | MATERIAL AND METHODS

The Amazon basin is formed by a great diversity of geological formations, with different strontium isotopic ratios ($^{87}\text{Sr}:^{86}\text{Sr}$), allowing to distinguish at least 3 large sub-basin categories (Figure 1): (1) the Western Andean tributaries (WAT), including the main channel of the Amazon River and its western floodplain tributaries (0.705–0.712); (2) the sub-basin of the Madeira River (0.714–0.726); and (3) the tributaries draining the Granitic Shields (GST) from Brazil and Guyana (0.724–0.744) (details on the compilation of these data in Hauser et al. [2019]). The small annual and seasonal variability of these isotopic ratios allows for the reconstruction of migratory patterns of fish that perform large displacements (Hauser et al., 2019), including natal homing in *B. rousseauxii* (Duponchelle et al., 2016; Hauser

et al., 2020). Briefly, individuals with mean $^{87}\text{Sr}:^{86}\text{Sr}$ ratio ≥ 0.714 close to the otolith core are classified as being hatched in the upper Madeira, while individuals with mean $^{87}\text{Sr}:^{86}\text{Sr}$ ratio ≤ 0.712 are classified as being hatched in the upper Amazon—the latter group being considered strayers if they were caught as adults in the upper Madeira (see Figure S1 for the different scenarios). Of the individuals hatched in the upper Madeira, those that have an $^{87}\text{Sr}:^{86}\text{Sr}$ ratio dropping below 0.714 a few hundred microns from the otolith core, remained in this signature range for a protracted period, and later returned to waters with signature ratio ≥ 0.714 are considered to be natal homers. Individuals with $^{87}\text{Sr}:^{86}\text{Sr}$ ratio staying ≥ 0.714 during their whole life are considered residents of the Madeira.

We sampled specimens (Figure 1) between February 2005 and March 2009 before the dams were built in the upper Madeira (Bolivia and Peru, 84 fish), to estimate the proportions of natal homers, natural residents, and strayers described in Duponchelle et al. (2016). We then sampled fish between April 2015 and October 2015, after the dams were built, in the upper Madeira to assess potential changes (58 fish). We further sampled in the estuary

between January 2015 and October 2015 (79 fish) to verify whether fish hatched in the upper Madeira could cross the reservoirs and dams and reach their nursery area. Finally, we sampled between August 2015 and June 2017 two strategic locations below the dams, below the confluence of the Madeira in Itacoatiara (eight fish) and just below the dams in Porto Velho (five fish), to check whether individuals hatched in the Madeira after the dams and that would reach the estuary could try to home back to their natal origin.

Two hundred and thirty-four fish (26–142 cm standard length [SL]) were sampled between February 2005 and June 2017 on main fish-landing sites along the Amazon Basin, from the headwaters in the Andean region (Peru and Bolivia) to the estuary at the mouth of the Atlantic Ocean (Brazilian Portion) (Figure 1), except in the estuary where small juveniles were brought to local landing sites, close to the fishing grounds. Each fish SL was measured (nearest cm) and otoliths (lapilli) were extracted, rinsed in clear water, dried, and stored dried for later examination. They were mounted in epoxy resin, and transverse sections to a thickness of approximately 0.7 mm were made with a low-speed Isomet saw (Buehler) to obtain a slice including the core. The section was then grounded and polished using polishing papers (1200 and 2400 μm) and ultrapure water until the core was seen on one side (Duponchelle et al., 2016; Hauser et al., 2019).

Analyses of Sr isotopes in otoliths were carried out in the laboratory LCABIE-IPREM (Université de Pau et des Pays de l'Adour, Pau, France) and in the laboratory PSO-IFREMER (Pole Spectrometrie Océan, Brest, France) (for details on the compatibility of results in both laboratories, see Hauser et al., 2019). Each otolith had a laser transect ablated from the core (birth) to the edge (death) perpendicular to the growth marks. Standard $^{87}\text{Sr}^{86}\text{Sr}$ certified otolith powder pellet (NIES22, certified Reference Material produced by the National Institute for Environmental Studies, Japan) was used between each opening of the ablation cell to check the reliability of $^{87}\text{Sr}^{86}\text{Sr}$ measurements (Yoshinaga et al., 2000). In all cases, fs-LA-MC-ICP-MS $^{87}\text{Sr}^{86}\text{Sr}$ measured values (mean $\pm$ 2 SD; LCABIE-IPREM-Pau = 0.709214 ± 0.000786 ; PSO-IFREMER-Brest = 0.709137 ± 0.000145) corresponded to certified values.

The minimum, medium, and maximum size at which juveniles *B. rousseauxii* left the Madeira River after birth in the headwaters, and at which the individuals returned as adults, were estimated from the regressions between the transversal radius of the otolith (R) and the SL of the individuals: $\text{SL} = 0.030845 \times R - 0.000093$ was used for individuals ≤ 45 cm and $\text{SL} = 70.545 \times \ln(R) - 469.65$ for individuals > 45 cm (Duponchelle et al., 2016). Considering the lengths obtained through the regressions,

the individual fish age was determined according to the von Bertalanffy growth function (VBGF): $\text{Age} = \{-\ln[1 - (\text{SL} \times \text{SL}_{\infty} - 1)] / K - 1\} + t_0$, where SL is the standard length estimated by the total radius of the otolith; $\text{SL}_{\infty} = 102.84$ cm is the asymptotic length; $K = 0.57$ is the growth coefficient of the fish; and $t_0 = 0.021$ is the theoretical age at which the length is zero. These last three parameters were obtained from the VBGF curve estimated for *B. rousseauxii* in the Madeira (Hauser et al., 2018).

Possible difference in the growth rate between homers (fish performing the classic natal homing pattern) and residents (fish that do not perform homing and remain their whole life in the Madeira waters) of the upper Madeira (the latter were divided into before and after the damming) was investigated by comparing the SL of individuals belonging to the more frequent age groups (2.5–3.4 and 3.5–4.4 years old), using two-sample t -tests (with two-tailed p -values) after verifying the normality and homoscedasticity of distributions.

3 | RESULTS

3.1 | Prevalent migratory patterns before the dams were built

Of the 84 individuals caught in the upper Madeira before the dams' construction (Figure 2a–c), 66 (79%) showed a typical three-phase pattern in their life cycle (Figure 2a). The first phase was marked by $^{87}\text{Sr}^{86}\text{Sr}$ values characteristic of the Madeira basin (0.714–0.726) in the nuclear region of the otolith, which corresponds to the hatching period. These values quickly dropped toward lower values typical of the Amazon basin (0.709–0.711). The second phase was characterized by a protracted period with these isotopic values of the Amazon. The third phase is characterized by the return to high $^{87}\text{Sr}^{86}\text{Sr}$ values characteristic of the Madeira basin. These fish were natal homers. On average, the fish analyzed exited the Madeira to enter the Amazon at ~ 39 days (~ 197 μm in otolith radius and 6.0 cm in SL; Table 1) and returned into Madeira waters at ~ 2.6 years (~ 2400 μm and 80 cm; Table 1). It is notable that once they had homed back, none of the 66 fish returned to the Amazon, as no isotopic values of the Amazon (0.709–0.711) were observed in their isotopic profile after their return.

Eleven fish (13%) had a single-phase profile with $^{87}\text{Sr}^{86}\text{Sr}$ values of the Madeira basin during their whole life, indicating residency (Figure 2b). Seven fish (8%) had a two-phase pattern with $^{87}\text{Sr}^{86}\text{Sr}$ values typical of the Amazon at hatching and during a protracted period of their life followed by values characteristic of the Madeira basin for the rest of their lives (Figure 2c). These seven individuals were strayers that remained in the Madeira between 3

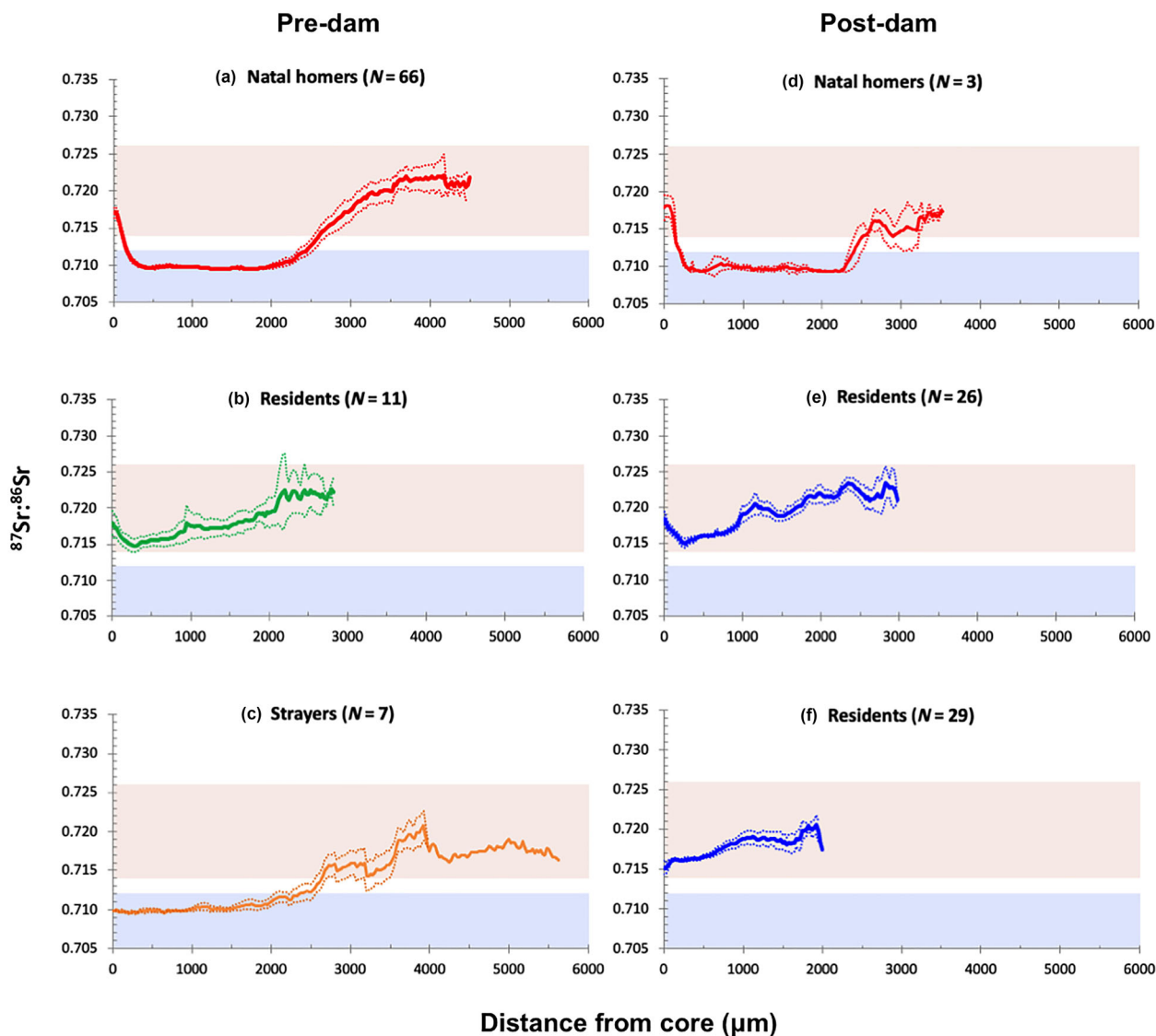


FIGURE 2 Prevalent migratory patterns of *Brachyplatystoma rousseauxii* in the Madeira basin before (a–c) and after (d–f) the construction of dams. Panel (e) refers to fish caught above Jirau dam and panel (f) to fish caught in the reservoir between the Jirau and San Antônio dams. All graphs represent the mean $^{87}\text{Sr}:^{86}\text{Sr}$ profiles of the specimens analyzed with their 95% confidence intervals. The horizontal translucent blue and red bands correspond to the range of $^{87}\text{Sr}:^{86}\text{Sr}$ water values in the Amazon main stem and Madeira basin, respectively. Individual profiles for all the fish used are available in Table S1. Note that one of the strayers from the upper Amazon was exceptionally old (18 years old), as the oldest fish previously observed in the Madeira were ~15 years old (Hauser et al., 2018).

TABLE 1 Characteristics (otolith radius, standard length [SL], and age) of the 66 *Brachyplatystoma rousseauxii* homers sampled before the dams were built at the exit phase from, and at the return phase to, the Madeira basin calculated from Figure 2a.

Exit from the Madeira			
	Otolith radius (μm)	SL (cm)	Age (days)
Minimum	110.0	3.4	21.5
Mean $\pm$ SD	196.5 $\pm$ 94	6.0 $\pm$ 2.9	39.0 $\pm$ 11.2
Maximum	750.0	23.1	162.2
Return to the Madeira			
	Otolith radius (μm)	SL (cm)	Age (years)
Minimum	1840	60.7	2
Mean $\pm$ SD	2422.6 $\pm$ 270.7	80.0 $\pm$ 8.3	2.6 $\pm$ 0.64
Maximum	2975	94.6	4.5

and 18 years (Table S1; sheet “Strayer Madeira BD”). The period of their life cycle at which these strayers entered the Madeira basin is extremely variable, ranging from about 6 months to ~9.5 years old (Table S1).

3.2 | Situation after the dams were built

A total of 58 individuals caught in the upper (above Jirau dam) and middle Madeira (above Santo Antônio dam) after the dams' construction were analyzed (Figure 2d–f). Only three specimens (5%) presented the prevalent natal homing pattern (Figure 2d). These three fish were large and old. They were caught between June and October 2015 in the Madre de Dios basin and were 5.4, 5.5, and 7.7 years old (Hauser et al., 2018). Hence, they were born in mid-2009 and 2007, and they homed back in the Madeira at ~2.5 years old, before Santo Antônio Energia dams' closure in September 2011.

The other 26 fish (45%) caught in the upper Madeira (19 specimens from the Madre de Dios basin and seven specimens from Guajara; Figure 1) presented a Sr isotopic profile indicating they had remained all their life cycle within the Madeira upstream of the Jirau dam (Figure 2e). These fish caught between April and October 2015 were, on average, 3.2 ± 0.6 years old (range: 1.9–4.5 years old); most of them were hatched after the dam's closure and did not pass the two series of reservoirs and turbines. Finally, 29 specimens (50%) all of which were <2 years old were caught in the reservoir upstream of Santo Antônio dam (Figure 2f). They too had a profile indicating they had never left the Madeira. We therefore consider these 55 fish (95%) as residents.

Within the main nursery area in the Amazon estuary, of the 79 juvenile fish caught in May and October 2015, 66 (83.5%) were hatched in the upper Amazon (mean age: 1.3 years $\pm$ 1 SD; range: 0.6–2.8 years) (Figure 3a) and 13 (16.5%) were hatched in the Madeira after the dams' closure (mean age: 1.4 years $\pm$ 0.8 SD; range: 0.7–3 years) (Figure 3b).

Out of the 8 fish sampled further upstream in the lower Amazon in Itacoatiara in August 2015, below the confluence between the Madeira and the Amazon (Figure 1), 5 were hatched in the upper Amazon (mean age: 1.5 years $\pm$ 0.6 SD; range: 1–2.3 years; Figure 3c) and 3 were hatched in the Madeira after the dams' closure (mean age: 1.4 years $\pm$ 0.5 SD; range: 0.9–2 years; Figure 3d).

In 2017, the five young specimens sampled in the Madeira close to Porto Velho, just below Santo Antônio dam (Figure 3e; mean age: 2.9 years $\pm$ 0.3 SD), were hatched in the upper Madeira after the dams were built (between February 2014 and October 2014). They reached their nursery areas in the lower Amazon estuarine region

(isotopic values ~0.710), where they spent a few years. Then they homed back to the Madeira (return to isotopic values above 0.714) and remained below the dams for 0.8 years on average (range: 0.2–1.4 years), where they were caught by fishers.

3.3 | Does residency entail different growth performances compared to homing?

Residents were only observed in two age classes, 3 (2.5–3.4) and 4 (3.5–4.4) years old. As no significant difference in length-at-age was observed between pre-dam and post-dam residents, these were pooled per age class for comparisons with natal homers (Figure 4). Within each age class, the fish that grew in the lower Amazon estuarine region (natal homers) were significantly larger than those that had spent their entire life cycle within the Madeira basin (resident fish) (*t*-test [two-tailed *p*-values]: *t* = 5.543 [29 d.f.], *p* < 0.001 for age class 3; *t* = 2.487 [19 d.f.], *p* = 0.022 for age class 4). Homers of age class 3 had a median SL of 96 cm (interquartile range [IQR]: 94–103 cm), whereas residents of the same age class had a median SL of 75 cm (IQR: 71.5–80 cm). Among age class 4, homers had a median SL of 98.5 cm (IQR: 95–103 cm), whereas residents had a median SL of 83 cm (IQR: 74.8–92 cm).

4 | DISCUSSION

Our results demonstrate that the Madeira dams have profoundly altered the migration patterns of *B. rousseauxii*, preventing pre-adult individuals from reaching their breeding grounds in the upper Madeira. Before the dams, the prevalent migratory pattern consisted of 79% natal homers, 13% residents, and 8% strayers. After the dams, only three out of the 58 fish analyzed had an isotopic profile corresponding to homers. These three fish, although caught after the dams' construction, were old fish that had time to complete their normal life cycle and to home back to the upper Madeira before the dams' completion. Therefore, of our sampled fish that were born in the upper Madeira after the dams, none of them showed isotopic signatures, indicating that they entered the Amazon after birth and homed back to the upper Madeira. Hence, these fish were residents (likely forced residents). By contrast, before the closure of dams, ~80% of individuals sampled were homers. Our results therefore demonstrate that the Madeira dams currently represent unpassable barriers to pre-adult *B. rousseauxii* trying to reach their upstream breeding grounds.

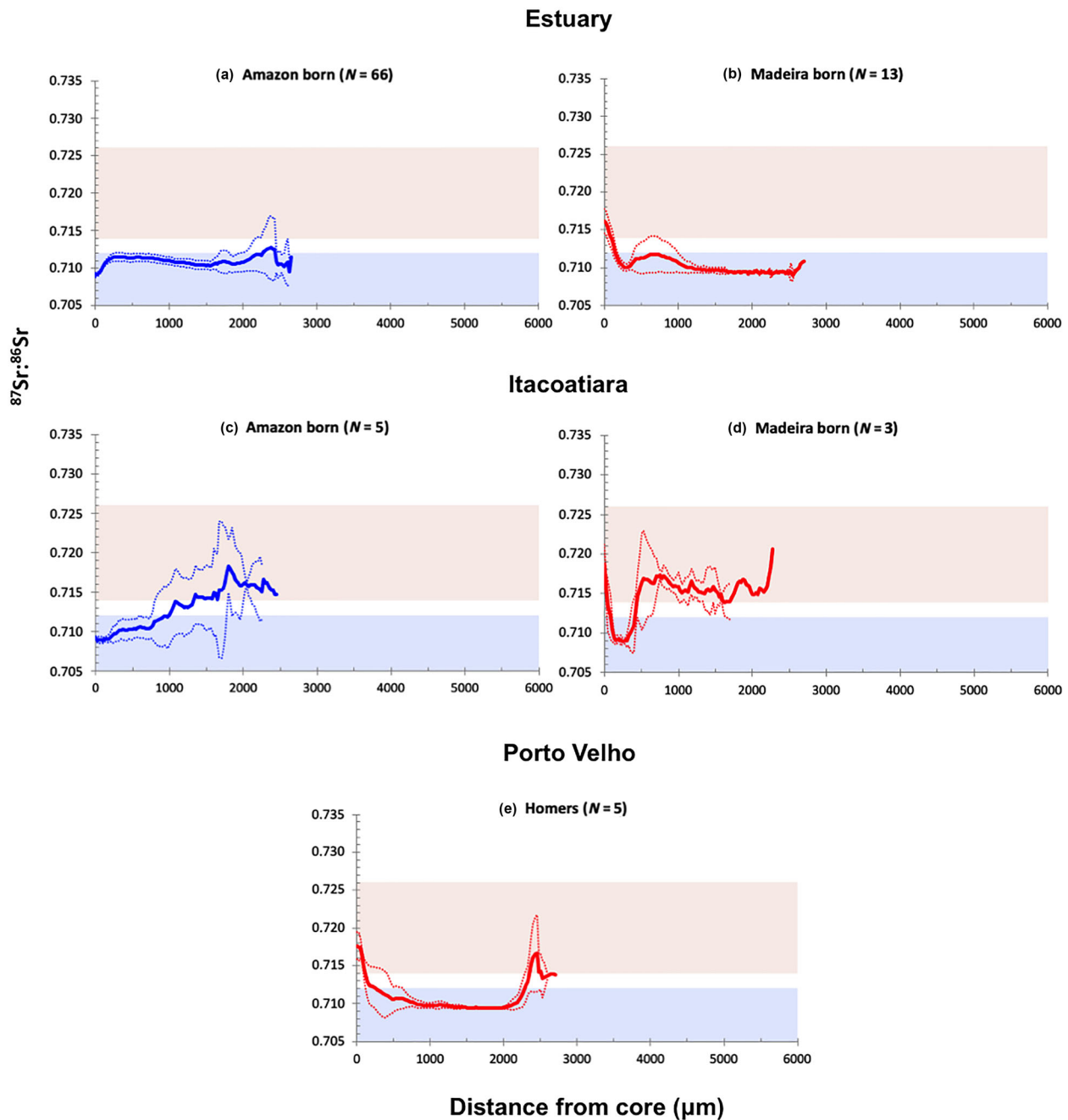


FIGURE 3 Mean $^{87}\text{Sr}:^{86}\text{Sr}$ profiles with their 95% confidence intervals of the specimens sampled in the estuary region (a, b), in Itacoatiara (c, d), and just below Santo Antônio Energy dam, close to Porto Velho (e). The horizontal translucent blue and red bands correspond to the range of $^{87}\text{Sr}:^{86}\text{Sr}$ water values in the Amazon main stem and Madeira basin, respectively. Individual profiles for all the fish used are available in Table S1.

The existence of naturally occurring resident behavior in the Madeira population of *B. rousseauxii* before the dams suggests that the species might adapt to the present landlocked conditions within the upper Madeira, as observed in other species around the world (Peller et al., 2023). The persistence of the species in the upper Madeira would require, however, that enough residents survive and that they could reproduce, two conditions for which there

is currently no evidence, as suggested by dramatically decreasing catches (van Damme et al., 2019). As already reported in other fish species (Gillanders et al., 2015), we also observed a significantly lower growth for resident individuals than for migratory ones. The important length-at-age decrease of the landlocked resident population is likely to negatively influence its reproductive output, as fecundity is positively related to body size and mass in *B.*

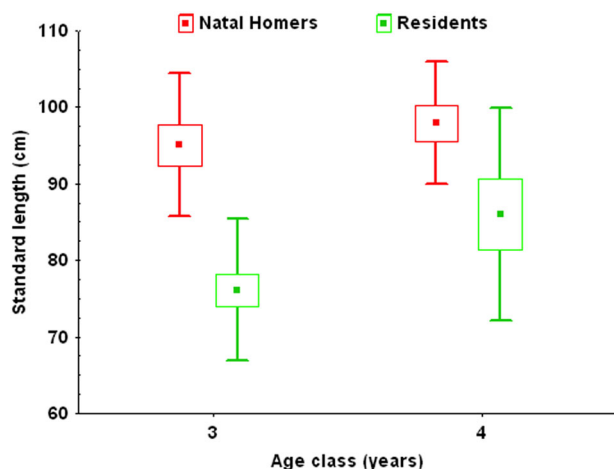


FIGURE 4 Mean length-at-age of *Brachyplatystoma rousseauxii* age groups 3 and 4 for natal homers and resident individuals in the upper Madeira basin. Small square: mean; box: mean $\pm$ SE; whisker: mean $\pm$ SD.

rousseauxii (Garcia-Vasquez et al., 2009). Current evidence therefore provides little hope as to the sustainability of the landlocked population in the upper Madeira.

Yet, our sampling in the lower Amazon reserved some surprises: Madeira-born juveniles sampled in the estuary. Available knowledge of the species' reproductive biology in the Madeira indicates that it only breeds in the Andean foothills in the Bolivian and Peruvian portions of the basin (Barthem et al., 2017; Cella-Ribeiro et al., 2015; Miranda-Chumacero et al., 2020). This suggests that despite the existence of two reservoirs and two sets of turbines on their way, some *B. rousseauxii* larvae still managed to survive their downstream journey from the hatching areas in the upper Madeira to the nursery areas in the lower Amazon estuarine region. Alternatively, we can hypothesize that reproduction could now take place somewhere below the dams in the Madeira, although there is currently no evidence to support it. Such a hypothesis is amenable to testing in future studies by analyzing the gonads of females caught below the dam and/or by sampling *B. rousseauxii* larvae below the dam and comparing their sizes to what was observed before the dams (Cella-Ribeiro et al., 2015). We do provide evidence, however, that these fish hatched in the Madeira after the dams were built, and the fish that managed to survive the industrial fisheries targeting the young *Brachyplatystoma* spp. in the estuarine region (Barthem & Goulding, 2007) tried to home back to the Madeira. Unfortunately, they remained blocked below Santo Antônio's dam. Additionally, none of the 55 fish caught and born upstream of the dams provided any evidence that these young homing adults could make their way up through Santo Antônio's fish transposition system, as no single fish born and caught in the upper Madeira after

the dams presented the usual pre-dam homing profile. Our results therefore provide compelling evidence that Santo Antônio's fishway (Jirau dam does not even have a fishway) is ineffective for facilitating their homing migration to the breeding areas of the upper Madeira, reinforcing previous results based on telemetry (Hahn et al., 2022).

Safeguarding and restoring freshwater connectivity is recognized worldwide as a priority conservation action to halt or at least slow down the rate of global freshwater biodiversity loss (Barbarossa et al., 2020; Tickner et al., 2020), including in the Amazon basin (Anderson et al., 2018; Castello et al., 2013). Although restoring lost migrations after re-establishing connectivity is possible, it is usually achieved through considerable efforts and investments (Barker et al., 2022), which are unlikely to occur in the largest river basin of the world, shared by several countries. Our results strongly suggest that the conservation of the declining (Cella-Ribeiro et al., 2017; Lima et al., 2020; Santos et al., 2018; van Damme et al., 2019) and already vulnerable population of the Madeira, according to IUCN Red List (Salvador et al., 2023), primarily requires the urgent re-establishment of the connectivity between the upper and lower portions of the Madeira by devising efficient fishways for both hydroelectric dams.

Two recent reviews on the conservation (Duponchelle et al., 2021) and the diversity (Herrera-R et al., 2023) of migratory fishes in the Amazon basin have synthesized the available knowledge on their ecology, migratory routes, threats, and economic importance. Goliath catfishes, and *B. rousseauxii* in particular, represent the extreme end of the long-distance migration spectrum and are even more susceptible to disruptions in connectivity than other migratory species. Nevertheless, improving their up- and downstream passage might also benefit other migratory catfishes and characids, which represent the vast majority of migratory species in the Amazon basin (Duponchelle et al., 2021; Herrera-R et al., 2023). As seen in other large river systems globally, reducing the fragmentation effect of dams requires the coordination of researchers, engineers, and dam operatives for devising selective fish passage systems that exploit species differences in physical ability, spawning behavior, and sensitivity to various sensory stimuli (Birnie-Gauvin et al., 2019; Silva et al., 2018; Wilkes et al., 2019). This requires promoting and financing further research on the ecology of migratory species (Barbarossa et al., 2020)—a crucial knowledge that is lacking for many Amazonian species (Duponchelle et al., 2021). Unfortunately, these conditions are seldom met, particularly in the tropics where the effectiveness of fishways for accommodating the migrations of multiple species groups has mostly failed, partly owing to conceptual issues and the lack of preservation of critical habitats on both sides of the dams (Birnie-Gauvin et al., 2019; Pelicice & Agostinho,

2008; Pelicice et al., 2015; Pompeu et al., 2012; Silva et al., 2018). As seen in Brazil, policies enforcing the construction of improperly planned fishways can even be detrimental to the population's viability (Pelicice et al., 2017). Our results on this emblematic species provide the scientific evidence needed to put strong institutional pressure on both energy companies for the urgent funding of the research and engineering efforts needed to build efficient fishways providing a safe passage for migratory fish while blocking the colonization of invasive species.

This is particularly important as under the planned hydroelectric development, most of the Andean sub-basins used as breeding grounds by *B. rousseauxii* (Barthem et al., 2017) will suffer even more important connectivity loss (Caldas et al., 2023). This calls for urgent conservation actions and particularly the implementation of effective fishways, as ecosystem modeling has confirmed the importance of *B. rousseauxii* for the stability of Amazonian aquatic ecosystems (Angelini et al., 2006), including in the Madeira River in both the pre- and post-dam periods (Lima et al., 2020). The present alterations in the migratory and growth patterns of this apex predator now landlocked within the upper Madeira will likely lead to important ecosystem changes, both locally and along its former migratory route, through trophic cascades (Bauer & Hoyle, 2014; Estes et al., 2011, 2016; Peller et al., 2023). As trophic cascades tend to be stronger where they involve large, mobile predators (Borer et al., 2005) such as *B. rousseauxii*, this could ultimately lead to a decreased stability and higher vulnerability of the ecosystem (Britten et al., 2014). Large piscine predators seldom exhibit long-range migrations in continental ecosystems; hence, the effects of damming on *B. rousseauxii* in the Amazon basin could have more severe impacts on the ichthyofauna and food webs (Duponchelle et al., 2016). This further emphasizes the need for considering, before dam construction, spatially explicit prioritization methods that trade off energy power and the conservation of biodiversity under different scenarios for large, species-rich, river basins such as the Amazon (Flecker et al., 2022).

AUTHOR CONTRIBUTIONS

Marília Hauser, Fabrice Duponchelle, Gislene Torrente-Vilara, Jean-François Renno, Carlos Edward Freitas, and Carolina R. C. Doria conceived the ideas. Marília Hauser and Fabrice Duponchelle designed the methodology. Marília Hauser, Fabrice Duponchelle, and Carmen García-Dávila collected the data. Marília Hauser, Fabrice Duponchelle, Christophe Pécheyran, Emmanuel Ponzevera, and Jacques Panfili performed microchemistry analyses and data workup. Marília Hauser, Fabrice Duponchelle, and Carolina R. C. Doria wrote the

manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data openly available in a public repository that issues datasets with DOIs.

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