

Conservation of migratory fishes in the Amazon basin

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Abstract :

1. The Amazon basin hosts the Earth's highest diversity of freshwater fish. Fish species have adapted to the basin's size and seasonal dynamics by displaying a broad range of migratory behaviour, but they are under increasing threats; however, no study to date has assessed threats and conservation of Amazonian migratory fishes.
2. Here, the available knowledge on the diversity of migratory behaviour in Amazonian fishes is synthesized, including the geographical scales at which they occur, their drivers and timing, and life stage at which they are performed.

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3. Migratory fishes are integral components of Amazonian society. They contribute about 93% (range 77–99%) of the fisheries landings in the basin, amounting to ~US\$436 million annually.
 4. These valuable fish populations are mainly threatened by growing trends of overexploitation, deforestation, climate change, and hydroelectric dam development. Most Amazonian migratory fish have key ecological roles as apex predators, ecological engineers, or seed-dispersal species. Reducing their population sizes could induce cascading effects with implications for ecosystem stability and associated services.
 5. Conserving Amazonian migratory fishes requires a broad portfolio of research, management, and conservation actions, within an ecosystem-based management framework at the basin scale. This would require trans-frontier coordination and recognition of the crucial importance of freshwater ecosystems and their connectivity.
 6. Existing areas where fishing is allowed could be coupled with a chain of freshwater protected areas. Management of commercial and subsistence species also needs fisheries activities to be monitored in the Amazonian cities and in the floodplain communities to allow assessments of the status of target species, and the identification of management units or stocks. Ensuring that existing and future fisheries management rules are effective implies the voluntary participation of fishers, which can be achieved by increasing the effectiveness and coverage of adaptive community-based management schemes.

Keywords : biodiversity, fisheries management, hydroelectric dams, overexploitation, societal importance, threats

94 **INTRODUCTION**

95 Recent reviews have shown that most migratory animals across the planet are
96 suffering major population declines, more so than related non-migratory species (Bauer &
97 Hoyer, 2014; Lennox et al., 2019). They also have emphasized the critical ecological role of
98 animal migrations for ecosystem stability and functioning, and the universality of the causes
99 driving their decline: habitat loss, barriers to migrations, overexploitation and climate change.
100 Animal migrations are notoriously difficult to define and classic examples involving large-
101 scale movements represent extreme cases rather than the rule (Dingle & Drake, 2007). Here,
102 based on Dingle & Drake (2007), Lucas & Baras (2001), and McIntyre et al. (2016),
103 migrations are considered as periodic or seasonal synchronized movements of adaptive value
104 (critical for individual fitness and population persistence) between two or more separate
105 habitats involving a large portion of the population and which are repeated within or across
106 generations. Migratory species rely on multiple, distant but inter-connected habitats during
107 their life cycle, which has been termed “triple jeopardy”, illustrating their dependence on at
108 least two distant habitats and on the corridor that relates them (McIntyre et al., 2016). Unlike
109 flying or terrestrial animals, the movement of freshwater fishes is highly constrained by the
110 linear and hierarchical structure of freshwater networks, and their migration corridors can be
111 easily blocked by anthropogenic causes. As a consequence, freshwater migratory fishes,
112 which sustain vitally important fisheries for millions of people across the world, are among
113 the most endangered of freshwater biota (Dudgeon et al., 2006).

114 Human impacts on fish migratory species are of growing concern in the Amazon
115 basin, which hosts the world’s highest freshwater fish species richness with 2406 species,
116 representing 15 % of the world’s freshwater fishes (Jézéquel et al., 2020). Nearly all
117 migratory fish species in the Amazon are considered to be potamodromous, migrating
118 between different and often distant freshwater habitats to complete their life cycles. Many

119 migratory movements are synchronized with the ‘flood pulse’ of Amazonian rivers (Junk,
120 Bayley & Sparks, 1989), which creates marked seasonal water level variations to which fish
121 species have adapted. The most conspicuous commercial species, such as the large and
122 medium-sized Characiforms (e.g., *Prochilodus*, *Collossoma*) and the large goliath catfishes
123 (e.g., *Brachyplatystoma*) perform medium- to long-distance migrations in the Amazon basin
124 that have received most of the attention to date (Barthem & Goulding, 1997; Carolsfeld,
125 Harvey, Ross & Baer, 2003). However, the species that perform seasonal synchronized
126 movements at local scales between the river channels and the flooded environments, such as
127 many floodplain species, can also be considered migratory as their non-random lateral
128 movements involve the repetitive use of separate habitats that are essential to their feeding
129 and reproductive success, hence to the completion of their life-cycles (Fernandes, 1997; Lucas
130 & Baras, 2001; Osorio et al., 2011; Winemiller & Jepsen, 1998).

131 Given the diversity of Amazon fishes, the complexity of their life cycles, and the
132 growing anthropogenic pressures, there is a major need to critically synthesize available
133 information to assess prospects for conserving Amazonian migratory fishes. This paper
134 addresses five questions: What is the diversity of migratory behaviours among Amazonian
135 fishes? What is the societal importance of migratory fishes in the Amazon basin? What
136 factors threaten migratory species in the Amazon basin? What are the potential ecosystem
137 impacts of extirpation or strongly reduced populations of migratory fishes in the Amazon
138 basin? And finally, what are the challenges in research, management and conservation to
139 preserve migratory species in the Amazon basin?

140

141 **Diversity of migratory behaviours in Amazonian fishes**

142 Diversity

143 The freshwater-strict fish fauna of the Amazon (without its coastal zones) contains an

144 estimated 2,406 valid species, including 1,402 endemic species representing 514 genera, 56
145 families, and 15 orders (Jézéquel et al., 2020). Of those, at least 172 species (~7.1% of all
146 species in the basin) belonging to 7 orders (~46.7%), 26 families (~46.4%) and 90 genera
147 (~17.5%) perform potamodromous migrations (Supplementary Table 1). Most migratory
148 species belong to the orders Characiformes (60.5%) and Siluriformes (29.7%).

149 Scales and types

150 The geographical scales of fish movements in the Amazon basin are often related to the
151 direction of their migrations, which can be longitudinal (long and medium distance) or lateral
152 (short distance) (Figure 1). Longitudinal migrations occur within the upstream-downstream
153 gradient of rivers in both directions and can connect different parts of a river (upstream with
154 downstream) or even the estuary and/or main river channels with the headwaters (e.g. Andes,
155 Precambrian shields) and/or smaller tributaries (e.g. terra firme streams). Lateral migrations
156 occur among habitats of river-floodplains, including the main river channels and lakes,
157 connecting channels and various vegetated habitats such as flooded forests (Fernandes, 1997;
158 Osorio et al., 2011). Whereas a few species only perform long-distance longitudinal migrations
159 (e.g., *Brachyplatystoma*), some species perform both longitudinal and lateral migrations (e.g.,
160 Characiformes), and some perform mainly lateral migrations (e.g., Osteoglossiformes).

161 The longest longitudinal migrations known in freshwater ecosystems are performed by
162 a group of large-bodied (1 – 3 m) goliath catfishes of the genus *Brachyplatystoma* (Barthem
163 & Goulding, 1997; Barthem et al., 2017; Hauser, 2018; Hauser et al., 2019). One species, *B.*
164 *rousseauxii*, performs a trans-Amazonian migration of up ~12,000 km round trip between its
165 hatching areas in the Andean piedmont of Bolivia, Colombia, Ecuador and Peru and its
166 nursery in the lower Amazon and estuary in Brazil (Barthem & Goulding, 1997; Barthem et
167 al., 2017). In this exceptional migration, most adult fish return to the geographic area (sub-
168 basin) where they were hatched (Duponchelle et al., 2016; Hauser et al., 2020), a process

169 called natal homing.

170 Intermediate migrations on the scale of hundreds of kms are performed by several
171 species of the orders Siluriformes, Characiformes, and Clupeiformes, for reproductive or
172 feeding purposes between the floodplains and river channel, headwaters and tributaries (see
173 synthesis by Araujo-Lima & Ruffino, 2003; Diaz-Sarmiento & Alvarez-León, 2003; Figure
174 1). Some of the best-documented examples of these migrations come from the
175 Prochilodontids. Juveniles of *Prochilodus nigricans* are estimated to travel a minimum of 500
176 km upstream from floodplains towards the Western Amazonia (Silva & Stewart, 2017).
177 Similarly, *Semaprochilodus* spp. travel up to 250 km upstream and downstream between
178 nutrient-poor water where they feed and white river channels where they reproduce in Central
179 Amazonia (Ribeiro & Petrere, 1990).

180 Short migrations of only a few km between habitats of the main river and the
181 floodplains are usually referred to as lateral migrations. They are performed by most
182 migratory Characiformes (Araujo-Lima & Ruffino, 2003; Diaz-Sarmiento & Alvarez-León,
183 2003; Fernandes, 1997; Goulding, 1980). Osteoglossiformes, such as *Arapaima* have been
184 shown to move synchronically through a total of eight distinct river-floodplain habitats over
185 the course of the flood pulse, closely following river water levels (Castello, 2008).

186 Drivers

187 Fish migrate for three main purposes: reproduction, feeding, and survival although
188 distinguishing between these drivers is often challenging (Lucas & Baras, 2001; McIntyre et
189 al., 2016). In the Amazon basin, fish migrations are intimately linked to seasonal fluctuations
190 of the hydrological regime (Goulding, 1980; Junk et al., 1989). Reproductive migrations of
191 many Characiformes species are synchronised with the rainy season and rising waters
192 presumably to optimize environmental conditions for the hatching of eggs, growth of larvae
193 and juveniles, and survival in general. Reproductive migrations can involve lateral movement

194 between main channels and floodplains, such as in some piranha species, which lay their eggs
195 on newly submerged vegetation (Uetanabaro, Wang & Abe, 1993). In longitudinal
196 reproductive migrations of Characiformes, adults of most species move downstream during
197 rising waters from nutrient-poor black or clear water tributaries into white water rivers main
198 stems to spawn (Araujo-Lima & Ruffino, 2003; Diaz-Sarmiento & Alvarez-León, 2003;
199 Ribeiro & Petrere, 1990). Longitudinal reproductive migrations of most large Siluriforms are
200 carried out upstream, towards the Andean piedmont (Barthem & Goulding, 1997; Barthem et
201 al., 2017; Duponchelle et al., 2016; Hauser et al., 2019, 2020). White water river mainstems
202 mainly serve as highways for larvae drifting into proper nursery grounds located downstream
203 in floodplains during the high-water season (Araujo-Lima & Oliveira, 1998; Lima & Araujo-
204 Lima, 2004). White water rivers floodplains and the estuary are also richer in nutrients and
205 more productive than black and clear water systems, offering better conditions as nursery
206 areas; juveniles of many migratory fish in the Amazon are only found in these habitats (Lima
207 & Araujo-Lima, 2004).

208 Feeding migrations occur mostly during high waters when, through lateral movements
209 adults of many frugivorous (e.g. Serrasalminae, Bryconidae) species enter into floodplains
210 during high waters to benefit from the newly available habitat and feed on fruits falling from
211 the inundated forest (Correa, Costa-Pereira, Fleming, Goulding, & Anderson, 2015).

212 Timing and fish life stages

213 Migrations occur at different life stages with different durations across the life span of
214 Amazonian fish species. The trans-Amazonian migration of juvenile and sub-adult
215 *Brachyplatystoma rousseauxii* from their nursery areas (in the Amazon estuary and lower
216 portion of the Amazon) to their adult feeding and breeding sites (in white water tributaries of
217 Bolivia, Colombia, Ecuador and Peru) is a unique event that lasts a couple years. Once there,
218 adults can move between different headwater tributaries but usually don't go back to central

219 or lower Amazonia (Duponchelle et al., 2016, Hauser, 2018; Hauser et al., 2018). Another
220 example, although this one lasts only a few weeks, is the ~400 km long upstream migration of
221 juvenile pencil catfish, *Trichomycterus barbouri*, or chipi chipi, from the floodplains of the
222 Beni River in Bolivia towards Andean foothill forest streams and rivers, where they will live
223 as adults (Miranda-Chumacero, Álvarez, Luna, Wallace & Painter, 2015). These examples are
224 two of the most extreme cases in the length-range of Amazonian migratory species: *B.*
225 *rousseauxii* is one of the largest species in the Amazon basin, reaching over 1.5 m, although it
226 usually does not surpass 1.1 m standard length during its trans-Amazonian migration (Hauser
227 et al., 2018), whereas *T. barbouri* measures no more than 3.3 cm when performing its
228 spectacular upstream migration, which represents a much bigger individual effort (Miranda-
229 Chumacero et al., 2015).

230 Reproductive and feeding seasonal migrations performed at the adult stage usually
231 occur on a yearly basis for most species, which potentially spawn multiple times during their
232 lives. Most migratory species in the Amazon basin are indeed iteroparous, as opposed to the
233 semelparous reproductive strategy that consists of a single reproductive event during the
234 lifetime, as exemplified by Gymnotiformes in the Amazon basin (Waddell et al., 2019) or
235 more classically by some salmon (Lucas & Baras, 2001). But some evidence suggests
236 patterns of migration can alter with age. In the Central Amazon, adults of *Semaprochilodus*
237 spp. travel between nutrient-poor tributaries and white rivers multiple times during the year.
238 However, some of the larger *Semaprochilodus* that usually reach the most western tributaries
239 no longer perform migration with age (Araujo-Lima, & Ruffino, 2003). This is also true for
240 some older *C. macropomum* that do not migrate upstream during low waters and stay in the
241 floodplains (Goulding & Carvalho, 1982).

242

243 **Societal importance of migratory fishes in the Amazon basin**

244 Freshwater fish have long been one of the most important protein sources for
245 Amazonian people. The historical and cultural importance of migratory species, as well as
246 their nutritional value and contribution to food security has been well documented (see
247 Supplementary material). What remains unclear is the contribution of migratory fishes to total
248 fish catch in the basin, although migratory Characiformes and Siluriformes represent about
249 83% (46% and 37%, respectively) of the annual commercial landings of migratory and non-
250 migratory fish species in the Amazon basin (Goulding et al., 2019).

251 Owing to the absence of official fisheries statistics in most Amazonian countries,
252 estimates of total Amazonian fish landings are far from complete. More than one decade ago,
253 the total commercial fisheries landings in the Amazon basin, excluding the Tapajós, Xingu
254 and upper Negro river basins, was estimated at 173,000 tons.year⁻¹ (Barthem & Goulding,
255 2007). Here, using this estimate and the approximate percentage contribution of the different
256 Amazonian regions provided by the same authors, the contribution of different categories of
257 migratory fish species in fisheries landings for the main Amazonian regions was estimated
258 (Table 1). Using such data, their current (2019) economic value was also estimated from the
259 mean price per kg of these species in the different regions (Figure 2). Long-distance
260 migratory fish, medium-distance large-sized Siluriformes, medium-distance large-sized
261 Characiformes, medium-distance small-sized species and short-distance or resident species
262 were distinguished, as these groups score different market prices.

263 For the portion of the fish catch that is landed in ports, migratory species averaged
264 ~93% of total landings in the Amazon basin (Table 1). However, there are marked regional
265 differences, with their contribution peaking at over 99% in the border between Brazil,
266 Colombia and Peru and being lowest in the clear water basins draining the Precambrian
267 shields such as the Tocantins River (~ 77%). The Amazon estuary, the Lower Amazon, Upper
268 Solimões, lower Tocantins and the Colombian Amazon fisheries have higher contributions of

269 Siluriformes species in the landings, whereas the Lower Solimões, Upper Amazon, Middle
270 Negro, Middle Madeira have more contribution of the Characiformes species (Table 1, Figure
271 2). The contribution of migratory species to fish landings, albeit still high, was relatively
272 lower in the upper Madeira in Bolivia (~ 81%, owing to the important contribution of the
273 introduced *Arapaima*). The introduced *Arapaima* spp. accounts for most of the short-distance
274 migrating or resident species (SD-R) landings in the upper Madeira.

275 According to Barthem et al. (1997), the fisheries sector in the Brazilian Amazon
276 generate a total yearly income between 100 and 200 million US\$ and employment for 168
277 thousand people, and migratory fishes are the major part of the catch. Van Damme, Carvajal-
278 Vallejos, Camacho, Muñoz & Coronel (2011) estimated the yearly monetary value of
279 migrating fish species in the Bolivian Amazon at about 3 million US\$. Here, total fisheries
280 landings in the Amazon basin represented over 470 million US\$ (Figure 2). Migratory species
281 of all four categories (excluding SD-R) average ~ 93% of total landings and therefore account
282 for approximately 436 out of the estimated 470 million US\$ provided annually by landed
283 Amazonian fisheries.

284 Much of the fish harvested in the Amazon, however, is consumed in riverine
285 communities and is never “landed” into markets, a phenomenon common to most inland
286 fisheries worldwide (Fluet-Chouinard, Funge-Smith & McIntyre, 2018). As an example, it is
287 estimated that almost 600,000 tons.year⁻¹ of fish are consumed throughout the Brazilian
288 Amazon (Isaac & Almeida, 2011) and 29,000 tons.year⁻¹ in the Colombian Amazon
289 (Agudelo, 2015), which together are about three times as much as the commercial landings
290 reported for the Amazon basin (Barthem & Goulding, 2007). Although fish consumed in
291 urban centers may partly come from marine fisheries or aquaculture, these figures indicate a
292 strong underestimation of actual Amazonian catches estimated by landing statistics (see also
293 Fluet-Chouinard et al., 2018). Estimates of these “hidden” subsistence fish catch vary, but

294 they are on the same order of magnitude, or more, as the estimates of fish landings provided
295 above (Crampton, Castello & Viana, 2004). Bayley (1998) used Batista, Inhamuns, Freitas &
296 Freire-Brasil (1998)'s data to re-estimate total fish catch in the Amazon basin at ~ 450,000
297 tons.year⁻¹. Although migratory species still dominate subsistence catches, some sedentary
298 species belonging to the Cichlidae and Loricariidae families can sometimes account for half
299 or more of the catches (Batista et al., 1998; Castello, McGrath & Beck, 2011; Castello,
300 McGrath, Arantes & Almeida, 2013). The figures provided here offer just a glimpse on the
301 importance of migratory fishes to Amazonian people, but further studies with current data that
302 also include subsistence fisheries will help with refining quantitative estimates of the
303 importance of migratory fishes to fisheries in the Amazon basin.

304

305 **Threats to migratory species in the Amazon basin**

306 The main threats to freshwater fish in the Amazon are similar to those menacing
307 freshwater biodiversity and fishes worldwide: overexploitation, flow and habitat modification
308 by hydropower development, deforestation and climate change (Carpenter, Stanley & Zanden,
309 2011; Dudgeon et al., 2006; Xenopoulos et al., 2005). Some acknowledged or potential
310 threats, such as pollution, waterways, non-native species or exploitation by the ornamental
311 trade are detailed in Supplementary material. Importantly, most of these threats interact
312 synergistically, further aggravating their individual impacts (see Anderson et al., 2019,
313 Forsberg et al., 2017; Lees, Peres, Fearnside, Schneider, & Zuanon 2016).

314 Overexploitation

315 Overharvesting has historically been the most important driver of freshwater
316 ecosystem degradation of the Amazon basin (Castello et al., 2013), and affects many
317 important migratory fish species. Catches of the largest, most commercial species, are
318 declining in most regions of the basin. This trend started with *Arapaima* spp. (Veríssimo,

319 1895), which was overharvested to the point of being placed in the CITES II list of
320 endangered species (Castello & Stewart, 2010; Castello, Stewart & Arantes, 2011). Although
321 basin-wide evidence of overfishing are still rare, over the last few decades, many trait-based
322 studies have offered evidence for regional overfishing of most large, high-valued species such
323 as the second largest scaled fish of the Amazon, *Colossoma macropomum* (Campos, Garcez,
324 Catarino, Costa & Freitas, 2015; Isaac & Ruffino, 1996), several large catfishes such as
325 *Brachyplatystoma vaillantii*, *B. rousseauxii* (Agudelo et al., 2013; Alonso & Pirker, 2005;
326 García-Vasquez et al., 2009), *Pseudoplatystoma tigrinum* and *P. fasciatum* (= *P. punctifer*,
327 Isaac, Ruffino & McGrath, 1998; Ruffino & Isaac, 1999), and *Pinirampus pirinampu*
328 (Sant’Anna, Doria & Freitas, 2014). Owing to their basin-wide migrations, *B. rousseauxii* and
329 *B. vaillantii* are particularly at risk: whereas their adult populations are already heavily fished
330 or overexploited in the lower (Cruz, 2020) and upper Amazon basin (Agudelo et al., 2013;
331 García-Vasquez et al., 2009; Petrere, Barthem, Agudelo & Gomez, 2004), juveniles of these
332 species currently support the largest Amazonian industrial fishery in the lower Amazon
333 (Alonso & Pirker, 2005; Barthem & Goulding, 2007). Overharvesting, however, is no longer
334 limited to large species and was recently also suggested to regionally affect some of the
335 smaller Characiformes that now make up most of the catches, such as *Prochilodus nigricans*
336 (Bonilla-Castillo, Agudelo, Gómez & Duponchelle, 2018; Catarino, Campos, Garcez &
337 Freitas, 2014) or *Psectrogaster* spp. (García-Vasquez, Vargas, Sánchez, Tello & Duponchelle,
338 2015).

339 The depletion of stocks of large-bodied species is the inevitable adjustment of tropical
340 fish communities to increasing fishing effort (Bayley & Petrere, 1989). This common
341 phenomenon in fisheries worldwide, where large, long-lived species are progressively
342 replaced in the landings by smaller short-lived species with higher production/biomass ratios,
343 is referred to as “fishing down” process (Welcomme, 1995) or “fishing down the food web”

344 process, which additionally predicts declining trophic levels in the catches (Pauly,
345 Christensen, Dalsgaard, Froese & Torres, 1998). The decline of mean catches of the largest
346 commercial species is already observed in several regions of the Amazon basin: in Brazil for
347 *C. macropomum* (Barthem et al., 1997; Garcez & Freitas, 2011), *Arapaima* spp. (Cavole,
348 Arantes & Castello, 2015; Castello & Stewart 2010), *B. filamentosum* (Petrere et al., 2004); in
349 Peru for several of the largest species such as *Arapaima* spp., *B. rousseauxii*, *C.*
350 *macropomum*, *Piaractus brachypomus* (García-Vasquez, Tello, Vargas & Duponchelle,
351 2009); in Colombia for *B. filamentosum*, *B. rousseauxii* and *Pseudoplatystoma* spp. (Agudelo,
352 Sánchez, Rodríguez, Bonilla-Castillo & Gómez, 2011). Declining mean size of target species
353 or increasing proportions of immature specimens in fisheries catches are also common signs
354 of overexploitation, although difficult to observe because they require accurate, though
355 seldom available, long-term size data (Froese, 2004). Castello et al. (2013) showed a strong,
356 historical decline in the mean lengths of harvested species between 1895 and 2007 in the
357 Brazilian Amazon. In the Colombian Amazon, the proportion of immature individuals in the
358 catches is frequently over 50% for many large catfishes, and these proportions have increased
359 in the last decades (Agudelo, Bonilla-Castillo, Gómez, Salvino & Trujillo, 2012). The same is
360 observed for *C. macropomum* (Garcez & Freitas, 2011) and *Arapaima* spp. (Cavole et al.,
361 2015) in Brazil.

362 Dams

363 There are currently about 158 hydroelectric dams in operation or under construction in
364 the Amazon basin and about 351 new dams are planned in the next 30 years, including 21
365 large dams below 400 m elevation (Almeida et al., 2019). Hydropower infrastructure building
366 is arguably the most rapidly growing threat, with important potential for connectivity
367 alteration and biodiversity loss, including in the Andean portion of the basin (Anderson et al.,
368 2018; Finer & Jenkins, 2012; Forsberg et al., 2017; Latrubesse et al., 2017; Latrubesse et al.,

369 in press).

370 Hydroelectric impoundments can impact migratory fishes at different scales, from local
371 extinction of species that cannot adapt to reservoirs and dam-tailwater conditions, to basin-
372 wide extirpations of migratory species (Freeman, Pringle, Greathouse & Freeman, 2003;
373 Pringle, Freeman & Freeman, 2000). The most evident effect of dams on Amazonian fishes is
374 the disruption of migration routes (Agostinho, Gomes, Santos, Ortega & Pelicice, 2016;
375 Ribeiro, Petrere & Juras, 1995; Santos, 1995). Although most studies were carried out in the
376 heavily fragmented Paraná and Paraguay basins, they show that despite financial investments
377 and engineering efforts in the construction of fish passes, these are largely ineffective in the
378 reestablishment of routes, free up-down movements of young and adults, and regional
379 recruitment (Agostinho et al., 2007; Lira et al., 2017; Pompeu, Agostinho & Pelicice, 2012).
380 In the Amazon basin, otolith microchemistry analyses provided clear evidence that fish passes
381 in the recent Jirau and Santo Antônio dams on the Madeira River currently do not permit
382 upstream passage of sub-adult *B. rousseauxii* returning from the lower Amazon estuary
383 (Hauser, 2018) and prevent former movement of *B. platynemum* between the upstream and
384 downstream reaches of the dams (Hauser et al., 2019).

385 Available evidence on the effect of dams mainly focuses on the large, long-distance
386 migratory species, which are usually most at risk (Agostinho et al. 2016; Arantes, Fitzgerald,
387 Hoeinghaus & Winemiller, 2019). For long-distance migrants such as goliath catfishes and
388 other longitudinal migrants, any dam on their migration routes will interfere by isolating their
389 breeding areas from feeding and nursery areas (Agostinho, Pelecice & Gomes, 2008; Ribeiro
390 et al., 1995), depleting resident populations above the dams, with unlikely long-term chances
391 of persistence (e.g. Hauser, 2018; Van Damme et al, 2019 for *B. rousseauxii* in the Madeira).
392 Large catfish fisheries usually decline upstream and downstream of dams, as was observed
393 above the Tucuruí dam on the Tocantins River (Ribeiro & Petrere, 1988; Ribeiro et al., 1995).

394 The same was observed below (Santos, Pinto-Coelho, Fonseca, Simões & Zanchi, 2018) and
395 above (van Damme et al., 2019) Jirau and Santo Antonio dams in the Madeira River. The
396 fisheries of smaller, mid-distance detritivorous and frugivorous migratory species first
397 increased in the river channels upstream and downstream of Tucuruí (Ribeiro et al., 1995) and
398 Peixe Angical dams in the Tocantins River shortly after their construction, but declined
399 afterwards (Monaghan, Agostinho, Pelicice & Soares, 2020). In the Jamari River, fisheries of
400 migratory Characiformes also strongly declined after Samuel dam (Santos, 1995).

401 Because Andean tributaries supply most (> 90%) of organic and inorganic materials
402 transported by Andean-origin lowland Amazonian rivers, they control various
403 geomorphological processes such as river meandering and floodplain formation in river
404 sections downstream (Filizola & Guyot, 2009; McClain & Naiman, 2008). Therefore, even
405 dams located upstream of fish migration routes can impact migratory species by reducing
406 sediment and nutrients supplies (Forsberg et al., 2017) and altering the hydrological migratory
407 cues and the physico-chemical spawning cues to which the fish are adapted (Agostinho et al.,
408 2008; Bailly, Agostinho & Suzuki, 2008; Freitas et al., 2012; McIntyre et al., 2016).
409 Modification of flow regime and especially of flood duration can also strongly impact
410 recruitment and juvenile survival in migratory species (Bailly et al., 2008). Alteration of
411 granulometry and geomorphology usually result in decreased abundance of bottom-feeding
412 species, such as the migratory Curimatidae, as observed below Samuel, Tucuruí and Itaipu
413 dams (Agostinho, Julio & Petrere, 1994; Santos, 1995). Channel morphology modifications
414 reduce the frequency of adjacent oxbow lakes and the connectivity with the floodplain,
415 together with reduced nutrient supply and thus decreased primary production (Forsberg et al.,
416 2017). This can also strongly impact the mid-distance migrants that are the primary and
417 secondary consumers making up the bulk of fisheries in the Amazon basin (i.e. most
418 commercial Characiformes species, see Barthem & Goulding, 2007). For example, the

419 collapse of the migratory planktivorous *Hypophthalmus* spp. fishery and general decreased
420 catches in the lower Tocantins River were attributed to a reduction in nutrient supply and
421 phytoplankton biomass following the Tucuruí dam construction (de Merona, Juras, dos Santos
422 & Cintra, 2010). By reducing downstream flood pulse variability, intensity and amplitude,
423 and by modifying geomorphology, dams also disrupt lateral connectivity between river
424 channels and floodplains (Forsberg et al., 2017): migratory fishes that seasonally migrate
425 laterally to floodplain habitats end up having less opportunities to colonize flooded forest
426 habitats that play key nursery and feeding roles, ultimately affecting fisheries (Castello, Isaac
427 & Thapa, 2015; Castello, Bayley, Fabre & Batista, 2019). For example, a 37% reduction in
428 maximum flooded area in the Loreto Region, Peru, following the construction of large dams
429 would result in an 88% decline in annual fish yield (Forsberg et al., 2017).

430 Newly formed reservoirs associated with the development of hydroelectric dam
431 construction usually change environmental conditions towards more lentic waters, which
432 favours non-migratory species at the expense of the former migratory species that populated
433 the river channels (Agostinho et al., 2008; Agostinho et al., 2016; Arantes, Fitzgerald,
434 Hoeninghaus & Winemiller, 2019). Another major impact of large reservoirs such as Tucuruí,
435 Balbina, Samuel or Sinop, is their strong filter effect on the movements of larvae and
436 juveniles of migratory species drifting downriver: these young stages, adapted to migrating in
437 running, oxygenated waters suddenly are faced with huge stagnant lake-like water bodies with
438 low oxygen concentration due to decomposing vegetation, and the presence of many
439 predatory species they do not normally encounter, such as piranhas and predatory cichlids
440 (Pelicice, Pompeu & Agostinho, 2015).

441 Deforestation

442 Deforestation is usually linked to agriculture and cattle ranching in the Amazon basin,
443 but is also frequently associated to other anthropogenic activities such as mining,

444 hydroelectric dams, and road building (Anderson et al., 2018; Forsberg et al., 2017; Lees et
445 al., 2016; Malhi et al., 2008). Its effects can differ within the impacted area and downstream.
446 Deforestation in the uplands typically increases water runoff and sediment loads carried
447 downstream by the rivers, altering geomorphological and biochemical processes with
448 consequences on soil erosion and biological productivity of aquatic ecosystems (Coe, Costa &
449 Soares-Filho, 2009). Local deforestation can have regional implications: strong deforestation
450 in the Tocantins and Araguaia basins resulted in increased water discharge by 25% and
451 shifted flood pulse timing by a month in these rivers (Coe et al., 2009). Increased flood
452 amplitude and decreased flood duration caused by local deforestation tend to augment erosion
453 in the river channels and reduce water transparency (Winemiller, Marrero & Taphorn, 1996).
454 More violent floods result in the washing out of substrate and associated benthic algae and
455 organisms on which migratory detritivores feed (Flecker, 1996). Adjacent lakes also tend to
456 become shallower and muddier by the increased sedimentation (Winemiller et al., 1996).
457 Reduced water transparency directly affects algal and zooplankton production in floodplain
458 lakes, which are important nursery areas for most Amazonian migratory and non-migratory
459 fish species (Pringle et al., 2000). In the Venezuelan Andean piedmont, where deforestation
460 was particularly acute and diminished connectivity with downstream floodplains, the
461 abundance of migratory fishes, including *Prochilodus* spp., was severely reduced (Winemiller
462 et al., 1996). Deforestation usually also reduces the input of large woody debris in local
463 streams, depleting fish species richness and abundance, including many migratory species,
464 with potential consequences for fisheries and ecosystems functions (Wright & Flecker, 2004).
465 Recent stable isotope analyses demonstrated that terrestrial plant materials and arthropods
466 were the most important items contributing to migratory fish biomass in the oligotrophic
467 Apaporis River floodplains in Colombia, emphasizing the importance of seasonally flooded
468 forests for sustaining fisheries in the Amazon basin (Correa & Winemiller, 2018). Negative

469 effects of deforestation on fish species richness, diversity, abundance (Arantes et al., 2018;
470 Freitas et al., 2018), biomass and functional diversity (Arantes et al., 2019), as well as on
471 fishery yield of migratory species (Castello, et al., 2018) have also been shown.

472 Climate change

473 Because they rely on multiple geographically separated habitats that are changing at
474 different rates and in different ways, migratory fish species will likely be strongly affected by
475 climate change with potential de-synchronization of the favourable conditions between the
476 starting and destination habitats (Lennox et al., 2019). Climate change in the Amazon basin is
477 expected to alter hydrological dynamics by changing patterns of rainfall (Castello & Macedo,
478 2016; Malhi et al., 2008, 2009). Increased discharge and extent of inundation are projected in
479 Western Amazonia, with the opposite trend in the Central and Eastern parts (Sorribas et al.,
480 2016). Also expected are increased frequency and intensity of extreme events, such as floods
481 and droughts (Zed et al., 2016). One of the first studies about climate change and its potential
482 impacts on Amazonian fishes predicted potential species loss of up to 12% in the Amazon and
483 23% for the Tocantins basins, although there was no indication of whether the species
484 affected were migratory or not (Xenopoulos et al., 2005). Reduced river discharge and
485 drought have been shown to affect fish population size-structure, community composition,
486 and reproduction (Frederico, Olden & Zuanon, 2016; Röpke et al., 2017, 2019). Hydrological
487 shifts, and river droughts in particular, can reduce the availability of migratory corridors
488 between critical habitats, such as river channels and floodplains, directly affecting migratory
489 species (Röpke et al., 2017). As water volume decreases, its temperature may increase and its
490 oxygen concentration drop, becoming detrimental or lethal for fish species (Ficke, Myrick &
491 Hansen, 2007; Frederico et al., 2016). As energy allocation in adult fish is divided between
492 maintenance metabolism, growth and reproduction (Wootton, 1998), increased amounts of
493 energy spent in compensating for unfavourable thermal conditions will come at the expense

494 of energy expenditures for growth and reproduction processes, while also increasing
495 susceptibility to disease (Ficke et al., 2007; Freitas et al., 2012). The toxicity of pollutants to
496 fish tends to increase with water temperature, and so is the bioaccumulation of mercury (see
497 Ficke et al., 2007). In lentic environments such as floodplain lakes, increased temperature
498 could enhance eutrophic conditions and stimulate explosive macrophyte development,
499 modifying food web dynamics and ultimately affecting the fishes that depend on them (Ficke
500 et al., 2007).

501 Potential range shifts of migratory species to cope with expected temperature increases
502 will be reduced or hampered by the fragmentation of river networks due to hydroelectric dams
503 and other infrastructure development in the Amazon basin (Myers et al., 2017). This situation
504 will likely be worse in the Andean portion of the basin, where most dams have been built or
505 are planned (Anderson et al., 2018), interacting with climate change to contract species ranges
506 and impeding them to reach suitable climate areas in some regions (Herrera-R et al. in press).

507 Global warming and reduced oxygen are also expected to significantly reduce fish
508 body size owing to fundamental ecological and metabolic principles (Cheung et al., 2013;
509 Sheridan & Bickford, 2011). Declining body size could also lead to ecosystem alteration
510 through trophic cascade for predatory species (Estes et al., 2011) or through disruption of
511 carbon flows for detritivorous species (Taylor, Flecker & Hall, 2006). The synergistic effects
512 of climate-driven and fishing-induced reductions of fish size could further aggravate such
513 potential impact.

514

515 **Potential ecosystem impacts of the loss of migratory species**

516 Most Amazonian migratory fish species have crucial ecological roles given their
517 functions as apex predators, ecological engineers, or seed-dispersal species. They often
518 provide significant subsidies from one component of the ecosystem to another so that the

519 depletion of their stocks or populations could have different but additive and potentially
520 marked consequences for Amazonian aquatic food webs.

521 Community-level studies have emphasized the crucial ecological role of top predators
522 in terrestrial and aquatic ecosystems (Estes et al., 2011; Heithaus, Frid, Wirsing & Worm,
523 2008). Top-down effects are expected in food webs when entire functional groups of
524 predators are depleted, as was demonstrated for several, often migratory, top predatory fish
525 species (Heithaus et al., 2008; Myers, Baum, Shepherd, Powers & Peterson, 2007). A similar
526 scenario is likely to happen with the decline of the large predatory catfish community of the
527 Amazon basin. ECOPATH models indicated strong cascading effects of the removal of the
528 largest *Brachyplatystoma* species, including an important biomass increase of their fish prey
529 with a concomitant decrease in invertebrate biomass and increase in macrophyte biomass
530 (Angelini, Fabr e & da Silva Jr., 2006; Lima, 2017). They also revealed that *B. rousseauxii*
531 was one of the most sensitive components, i.e. responsible for major ecosystemic alteration in
532 case of stock depletion. Trophic cascades are strongest where they involve large, mobile
533 vertebrate predators (Borer et al., 2005). There is thus little doubt that the decline of large
534 long-distance migratory catfishes will have profound effects on the structure and function of
535 food webs of the Amazon basin.

536 Migratory fishes are known to provide trophic subsidies to different river systems, and
537 can strongly influence the structure of local habitats and communities through feeding and
538 breeding activities (Bauer & Hoyer 2014). Despite the existence of highly diversified
539 migratory fish communities, including long-distance migrations, the role of fish movements
540 in nutrient transport and their effects on local food webs has received little attention so far in
541 the Amazon basin, particularly for large predators (Winemiler & Jepsen, 1998). There is
542 evidence, however, that middle-sized migratory species of the family Prochilodontidae have a
543 significant role in Amazonian food web dynamics. Prochilodontid fish of the genera

544 *Prochilodus* and *Semaprochilodus* feed on detritus, algae and associated microorganisms and
545 are important preys for larger piscivorous species (Hoeinghaus, Winemiller, Layman,
546 Arrington & Jepsen, 2006). Experimental in situ exclusions and enclosure of *Prochilodus*
547 *mariae* in Venezuela resulted in major changes on benthic organic matter and algal and
548 invertebrate communities, and hence in community and ecosystem attributes (Flecker, 1996;
549 Taylor, Flecker & Hall, 2006). These studies demonstrated that *Prochilodus* are functionally
550 dominant, engineering species capable of structurally modifying their habitats and influencing
551 pathways of energy and nutrient flux in ecosystems. Prochilodontids also perform complex
552 large-scale migrations between different river systems, migrating to rich floodplains during
553 high waters for spawning and returning to often nutrient-poor tributaries in the low water
554 period (Ribeiro & Petrere, 1990). As such, these migratory detritivores play important roles in
555 energy and biomass transfer to species higher in the food chain, providing subsidies that allow
556 larger piscivores to support higher population densities than would normally be possible in
557 oligotrophic waters (Hoeinghaus et al., 2006; Winemiller & Jepsen, 1998). They also allow
558 increased ecological efficiency and the connection of food webs over different spatial scales
559 (Hoeinghaus et al., 2006; Winemiller & Jepsen, 1998). Besides *Prochilodus* and
560 *Semaprochilodus* spp., several other migratory characiform species feeding relatively low on
561 the food chains, such as *Anodus* spp., *Brycon* spp., *Colossoma macropomum*, *Mylossoma*
562 spp., *Triportheus* spp. only reproduce in whitewater rivers, whereas they inhabit all types of
563 water as adults (Lima & Araujo-Lima, 2004). This transfer of basic primary production by
564 migratory species from nutrient-rich whitewater rivers into oligotrophic (clear or black
565 waters) ecosystems might therefore be a widespread phenomenon in the Amazon basin.

566 Another crucial ecological aspect of many Amazonian migratory fishes is their
567 frugivory and associated ability to disperse seeds (ichthyochory) and improve their
568 germination process, participating in the spatial distribution and assemblage diversity of

569 riparian forests (see Correa, Costa-Pereira, Fleming, Goulding, & Anderson, 2015 for
570 review). Although seed dispersal was initially believed to be ensured essentially by birds and
571 mammals, the last few decades have provided strong evidence that fishes are major actors of
572 this process (e.g. Correa, Winemiller, López-Fernández, & Galetti, 2007; Correa, Costa-
573 Pereira, Fleming, Goulding, & Anderson, 2015; Goulding, 1980; Horn et al., 2011) and may
574 have been the first vertebrate dispersers in the Neotropics 70 M years ago (Correa, Costa-
575 Pereira, Fleming, Goulding, & Anderson, 2015). As most tree species fruit during the high
576 water season, when fish invade the flooded forest to feed, seed dispersal is likely the result of
577 a long process of mutually beneficial co-adaptation (Correa, Costa-Pereira, Fleming,
578 Goulding, & Anderson, 2015; Goulding, 1980; Ferreira, Piedade, Wittmann & Franco, 2010).
579 There are approximately 150 known frugivorous fish species from 17 families and 6 orders in
580 the Neotropics (Horn et al. 2011), most of which occurring in the Amazon basin. These fish
581 species consume at least 566 species of fruits and seeds from 82 plant families (Correa,
582 Costa-Pereira, Fleming, Goulding, & Anderson, 2015). As the most effective seed dispersal
583 agents are large-bodied fish species, which are the most targeted by fisheries (Correa, Costa-
584 Pereira, Fleming, Goulding, & Anderson, 2015), fish overharvesting can potentially also
585 threaten plant biodiversity and conservation (Correa et al., 2015).

586

587 **Challenges in research, management and conservation**

588 Considering the diversity of fish migrations and the scales at which they occur in the
589 Amazon basin, conservation of migratory fish species would ideally require the
590 implementation of a riverscape approach, similar to that proposed by Fausch, Torgersen,
591 Baxter & Li (2002). However, given the state of ecological knowledge, the growing human
592 pressures on the natural resources (water, fish and other aquatic biota), and the lack of
593 environmental commitment and coordination between government agencies of Amazonian

594 countries, advocating only for such a comprehensive approach would be utopic. Tackling this
595 challenge calls for a more pragmatic approach setting different levels of possible actions.

596 Research

597 Whereas fisheries statistics have been historically collected in some of the main
598 fishing areas (Manaus, Santarém, Belém, Iquitos, Pucallpa and Puerto Maldonado in Peru,
599 Leticia and Puerto Leguizamo in Colombia), many such data collection systems no longer
600 exist. This scarcity of data collection represents a major challenge to conservation by
601 preventing assessments of fish population status. There is a major need to monitor fisheries
602 activities (landings by species, size distributions) not only in all urban centres, but also in
603 riverine fishing communities where a large portion of the catch is consumed. Improving our
604 knowledge on the migratory behaviour of most species is also a prerequisite to design
605 appropriate conservation measures in the face of growing anthropogenic pressures. Ecological
606 information regarding routes, habitats use, timing and environmental conditions are missing
607 for most migratory species in the Amazon. Several recent studies mentioned in this review are
608 using new otolith microchemistry or improved telemetry technics that bring new possibilities
609 to complement traditional approaches in understanding migratory patterns (see Hermann et
610 al., this issue). The use of these techniques should be encouraged.

611 In addition to improved knowledge of fish migratory behaviour, perhaps the greatest
612 need lies in identifying management units (i.e., stock definition), for all exploited taxa. Such a
613 goal is presently daunting, given the general scarcity of fisheries monitoring data and
614 population genetic studies. That scarcity is only matched by a generalized paucity of
615 researchers and investments in research on Amazonian fishes. There is therefore a major need
616 for boosting research via increased availability of fundings and incentives to work on
617 Amazonian fishes.

618 Management

619 For fishes that are harvested for commercial or subsistence purposes, a key challenge
620 is ensuring compliance with existing management limits. Management of such species
621 currently is almost entirely based on restrictive measures such as minimum size of fish, gears
622 and mesh size limitations, closed season and areas, quotas and control of access. Minimum
623 size measures are followed in fisheries with a specific target, like the *Arapaima* fishery in
624 managed lakes or the *Brachyplatystoma* trawl fishery in the estuary (Barthem, Silva-Júnior,
625 Raseira, Goulding & Venticinque, 2019). But they are almost impossible to implement in all
626 fisheries given the multi-gear and multi-species nature of Amazonian fisheries, the vast areas
627 involved, and the severe underfunding and understaffing of management agencies responsible
628 for fisheries. For *Arapaima*, nearly 77% of the catch in weight in the lower Amazon region
629 has been estimated to be illegal (Cavole et al., 2015). Spawn-at-least-once limits such as size
630 and season limits are among the most important management measures because they ensure
631 stock recruitment (Myers & Mertz, 1998). The usefulness of closed season is debated in the
632 Amazon. It is often associated with monetary compensation for fishers in Brazil, which can
633 have negative effects as a measure to protect fish stocks (Corrêa, Kahn & Freitas, 2014).
634 Owing to the complexity of many species' migratory behaviors, the choice of the closed
635 season is complicated and considered of little value in Central Amazon fisheries, where most
636 commercial fish species reproduce during the flooding period and are much less accessible to
637 fishing gears than during the low water period (Barthem et al., 2019; Ribeiro & Petrere,
638 1990). Yet, previous studies on overfished stocks of Amazonian migratory species have
639 suggested that compliance with existing size and season limits would recover those stocks
640 (Isaac & Ruffino, 1996; Castello, Stewart & Arantes, 2011; Castello, Bayley, Fabré & Batista,
641 2019). Recently, a five years complete fishing interdiction for *C. macropomum* was proposed
642 to foster stock recovery (Barthem et al., 2019).

643 Over the last three to four decades, community-based management (CBM) has grown

644 to encompass numerous communities in virtually all rivers of the Amazon and represents a
645 major conservation movement. CBM has proved an effective tool for mitigating threats on
646 some migratory species, such as *Prochilodus nigricans* (Anderson, Montoya, Soto, Flores &
647 McClain, 2009), *Colossoma macropomum* (Arantes & Freitas, 2016), and especially on
648 *Arapaima*. There are now ~ 500 fishing communities implementing CBM for *Arapaima* in the
649 Amazonas state alone (Campos-Silva, Hawes & Peres, 2019). Where studies have been done,
650 populations of *Arapaima* and of other migratory species have recovered from overexploitation
651 by increasing abundance (e.g., Campos-Silva & Peres, 2016; Campos-Silva et al., 2019;
652 Castello et al., 2019). Catch per unit effort (CPUE) is also generally higher in lakes with
653 CBM than in lakes without, as is mean body length of target species, including long-distance
654 migratory species even though these management schemes are at the small, local scale
655 (Almeida, Lorenzen & McGrath, 2009; Castello, Stewart & Arantes, 2011). As CBM often
656 involves conservation of floodplain habitats, it provides benefits to migratory species that
657 depend on floodplain habitats (Isaac, Ruffino & McGrath, 1998). Limiting fishing and
658 implementing reserves in the floodplains, where most migratory species spend critical part of
659 their lives, could also be a complementary solution (Barthem et al., 1997). The conservation
660 of migratory fishes therefore requires strengthening and further supporting the development
661 not only of CBM schemes but also of centralized government agencies.

662 A detailed, integrated management system for goliath catfishes (*B. rousseauxii* and *B.*
663 *vaillantii*) have previously been proposed for Brasil (Fabr e, Barthem, Carvalho & Angelini,
664 2005), including the estuary where most exploited individuals are immature, but only very
665 few of its recommendations were implemented so far. For long-lived migratory species, the
666 effects of overfishing could be reduced via use of simple indicators that have been proposed
667 as alternatives to conventional stock assessment models: the median length of catches, the
668 proportion of mature individuals in the catches, the proportion of fish caught at the optimum

669 length and the percentage of old, large individuals (“mega-spawners”, Froese, 2004). The
670 proportion of these mega-spawners in the catches draws on the increasing evidence that in
671 long-lived, late maturing species, large, old fish play major roles in the persistence of a
672 population (Berkeley, Chapman & Sogard, 2004; Froese, 2004; Birkeland & Dayton, 2005).
673 Ideally, there should be no single mega-spawner in the catches. However, in complex multi-
674 species fisheries such as those of the Amazon basin, mesh-size regulation would not be
675 effective to reduce the upper-size limit of catch for many species. Ensuring to keep
676 proportions of 30-40% of megaspawners in fisheries landings, which reflect a healthy stock
677 (Froese, 2004), might be a more practical solution. In Peru (Garcia Vasquez A., unpublished
678 data) and some locations in Colombia too, the largest *Brachyplatystoma* specimens are angled
679 by hook and line, which may allow for specific management strategies to achieve this goal.
680 Again, this would require the implementation, in all countries, of appropriate fisheries
681 statistics (catch and effort) including length monitoring on selected few target species, in
682 order to assess the effect of the proposed solutions. The targeted species could change every
683 two years so as to have good statistics to monitor the stock health every four to six years for
684 each large target species.

685 The ecosystem-based fisheries management that is internationally proposed for marine
686 resources (Pikitch et al., 2004) could also help conserve medium and long-distance migratory
687 fish species of the Amazon. Ecosystem-based fisheries management has two main goals:
688 satisfying societal and human needs for food and economic benefits while conserving the
689 structure, diversity, and functioning of ecosystems. Such an approach has been promoted in
690 the Amazon through two main mechanisms: community-based (see above) and basin-wide
691 managements. The basin-wide approach to ecosystem-based fisheries management uses
692 iconic long- and medium-distance migratory goliath catfishes and characins species. Goulding
693 et al. (2019) proposed to use the particular life histories of these migratory species to link

694 crucial spawning, feeding and nursery habitats across vast environmental connectivity
695 gradients in the Amazon basin: from Andean tributaries, lowland rivers and their floodplains,
696 down to the Amazon estuary. They advocated that the basin scale is the appropriate
697 framework for ecosystem-based management of fisheries in the Amazon and its wetlands and
698 emphasized the need of maintaining hydrological connectivity in the Amazon basin. This can
699 only be achieved through the recognition of the crucial importance of freshwater ecosystems
700 and their connectivity at the whole Amazon basin scale, which implies trans-frontier
701 coordination. Harmonized management of transboundary waters is recognized as a priority
702 (Castello et al., 2013; Pelicice et al., 2017), and the Amazon Cooperation Treaty Organization
703 might be the right place to propose solutions (Latrubesse et al., 2017).

704 Conservation

705 Not even the best available research and fisheries management framework can alone
706 conserve Amazon migratory fishes in the face of current trends of deforestation, climate and
707 hydrological change, and construction of dams. There is a major need to minimize, and to the
708 extent possible avoid, the adverse impacts that such trends are producing. As discussed
709 elsewhere, however, there are no basin-wide coordinated efforts to assess and manage the
710 progression of such threats on aquatic ecosystems of the Amazon. There are policies relevant
711 for aquatic conservation in most countries of the basin, including protected areas, regulation
712 on forests in private properties, water resource management, and environmental licensing of
713 hydropower dams. But together these policies have limited capacity to curb current trends
714 largely because they ignore the role of hydrological connectivity in freshwater ecosystem
715 structure and function (Anderson et al., 2019; Castello & Macedo, 2016; Leal et al., 2020).

716 Although to some extent the numerous protected areas can be seen as the paradigm in
717 Amazon conservation, they were primarily designed to preserve terrestrial ecosystems and are
718 largely ineffective to protect aquatic ecosystems and biota (Azevedo-Santos et al., 2019;

719 Castello et al., 2013; Frederico, Zuanon & De Marco, 2018; Leal et al., 2020). This situation
720 also holds true for the Andean portion of the basin (Anderson et al., 2019), where the
721 breeding grounds of many migratory species are located. There are very few aquatic reserves
722 in the Amazon basin, such as Mamirauá and Piagaçu-Purus in Brazil and Pacaya-Samiria in
723 Peru, which have proved effective in replenishing the populations of overexploited migratory
724 species such as *Arapaima* or *C. macropopum* (Arantes & Freitas, 2016; Ortega & Hidalgo,
725 2008). Nevertheless, important habitats for the life cycle of migratory fishes, such as
726 spawning, nursery and feeding areas, are currently not protected. The whitewater river
727 floodplains are the most important habitats for commercial migratory fish species, but less
728 than 1% is under integral protection and 15% are under some level of management (Goulding
729 et al., 2019). Encounters between whitewater and clearwater or blackwater tributaries are
730 other very important areas for migratory species that might warrant inventory and protection
731 (Barthem et al., 2019). The Amazon estuary, which hold crucial nursery areas for goliath
732 catfishes should also be a major target for conservation, but again, most of the detailed
733 recommandations provided in the integrated management system proposed by Fabr e,
734 Barthem, Carvalho and Angelini (2005) are not implemented. Owing to the connected nature
735 of river networks, reserves, even when they are effective at preserving freshwater biota,
736 remain highly susceptible to anthropogenic activities occurring upstream in the watershed,
737 such as damming, deforestation, pollution, etc. (Fausch et al., 2002). Anthropogenic
738 disturbances downstream can also have effects far upstream, through the action of migratory
739 species (Fausch et al., 2002).

740 New studies have evaluated whether it is possible to create new protected areas
741 (Frederico et al., 2018; Azevedo-Santos et al., 2019) or re-draw protected area boundaries to
742 improve protection on freshwater ecosystems. Creation of chains of protected areas could
743 help maintain most migratory species by protecting them from harvest and protecting their

744 habitats in various locations across the basin (Barthem et al., 1997; Bayley & Petrere, 1989;
745 Crampton et al., 2004; Hurd et al., 2016). A recent study demonstrated that taking into
746 account both terrestrial and freshwater biodiversity data for conservation planning could
747 vastly improve benefits for freshwater biodiversity (including fish), with only negligible
748 losses for terrestrial biodiversity (Leal et al., 2020). However, although the need for such re-
749 evaluations is clear, there is no effort to our knowledge to enable them. In fact, many
750 protected areas in the Amazon have been and continue to be reclassified and degazetted
751 (Anderson et al., 2018), further limiting their effectiveness with respect to migratory fishes.
752 Considerations about hydropower development in the Amazon basin

753 One of the most important issues highlighted in the present review, as in previous
754 studies (Anderson et al., 2018; Castello et al., 2013; Hurd et al., 2016), is the urgent need to
755 preserve aquatic natural flow regime and connectivity among river basins and between river
756 channels and their floodplains. However, even the best fisheries regulations, provided they are
757 enforced, will not be effective if dams disrupt river flow regime and connectivity. Dams also
758 promote deforestation, which in turn further favours climate change. Because the main driver
759 of aquatic connectivity disruption is the construction of dams, the conservation of the
760 Amazon aquatic biota, of migratory fishes in particular, and of the many ecosystem services
761 they provide requires regional re-consideration of the sustainability of large-scale
762 hydroelectric development in the Amazon basin and halting hydropower expansion. There are
763 cleaner, cheaper alternative energy sources for Amazonian countries, which are likely to
764 become even more cost-effective in the near future with technological development and under
765 the projected climate changes (Kahn, Freitas & Petrere, 2014). Dam development in the
766 Amazon basin, when unavoidable, should at least be carried out considering spatially explicit
767 prioritisation methods that trade-off energy power and biodiversity loss under different
768 scenarios (Almeida et al., 2019; McIntyre et al., 2016; Ziv, Baran, Nam, Rodríguez-Iturbe &

769 Levin, 2012) in order to lower environmental costs. In river basins already affected by dams,
770 accumulated evidence emphasizes the imperative necessity of preserving free-flowing
771 tributaries for maintaining reproduction of migratory fish (Casarim, Prado, Loures & Pompeu,
772 2018; Marques, Dias, Perbiche-Neves, Kashiwaqui & Ramos, 2018).

773 In the Amazon basin, environmental impact studies prior to infrastructure building
774 were usually not conducted for existing dams because these were built before baseline data
775 was available (Castello et al., 2013). As for the newly erected ones, they are seldom properly
776 done, with insufficient planning, funding, and realization time. Additionally, environmental
777 impact studies should be carried out by renowned public universities and research institutes
778 instead of private consulting firms in order to ensure the independency of results from
779 conflicting interests. For already constructed hydropower plants, such as the Madeira or
780 Tocantins dams, there is an urgent need to modify fishways technology to ensure a safe
781 passage to migratory fish species, while blocking the colonisation of invasive species. This
782 can only be achieved through coordination of researchers, engineers, and dam operatives to
783 develop adhoc technologies adapted to Amazonian species. In other parts of the world, many
784 recent research efforts have focused on reducing the fragmentation effect of dams by devising
785 selective fish passage systems that exploit species differences in physical ability, spawning
786 behavior, and sensitivity to various sensory stimuli (Birnie-Gauvin, Franklin, Wilkes &
787 Aarestrup, 2019; Silva et al., 2018; Lennox et al., 2019). In the Amazon basin, where such
788 technology is not available and where fish pathways are currently ineffective, governments
789 should foster strong investments in research and engineering projects focusing on similar
790 approaches. This, in turn, requires promoting and financing further research on the ecology of
791 many migratory species as such knowledge is an unavoidable prerequisite to successful
792 fishways (Pompeu et al., 2012; Silva et al., 2018) and to the establishment of conservation
793 measures (Barthem et al., 2019).

794

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796

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809 **REFERENCES**

- 810 Agostinho, A. A., Gomes, L. C., Santos, N. C. L., Ortega, J. C. G., & Pelicice, F. M. (2016). Fish
811 assemblages in Neotropical reservoirs: Colonization patterns, impacts and management.
812 *Fisheries Research*, 173, 26-36. doi:<https://doi.org/10.1016/j.fishres.2015.04.006>
- 813 Agostinho, A. A., Julio JR., H. F., & Petrere Jr., M. (1994). Itaipu reservoir (Brazil): impacts of the
814 impoundment on the fish fauna and fisheries. In J. G. Cowx (Ed.), *Rehabilitation of freshwater*
815 *fisheries*. (pp. 171-184).
- 816 Agostinho, A. A., Marques, E. E., Agostinho, C. S., Almeida, D. A. d., Oliveira, R. J. d., & Melo, J.
817 R. B. d. (2007). Fish ladder of Lajeado Dam: migrations on one-way routes? *Neotropical*
818 *Ichthyology*, 5, 121-130. doi:<https://doi.org/10.1590/S1679-62252007000200005>

819 Agostinho, A. A. I., Pelicice, F. M., & Gomes, L. C. (2008). Dams and the fish fauna of the
820 Neotropical region: impacts and management related to diversity and fisheries. *Brazilian*
821 *Journal of Biology*, 68, 1119-1132. doi:<https://doi.org/10.1590/S1519-69842008000500019>

822 Agudelo, E. (2015). *Bases científicas para contribuir a la gestion de la pesquería comercial de*
823 *bagres (familia: Pimelodidae) en la Amazonía colombiana y sus zonas de frontera.* (PhD
824 Thesis), Universidad Autónoma de Barcelona, Barcelona.

825 Agudelo, E., Bonilla-Castillo, C. A., Gómez Hurtado, G. A., Salvino Cruz, H., & Trujillo Yucuna, D.
826 L. (2012). Evolución de las longitudes corporales para la pesquería comercial de bagres en la
827 amazonia colombiana (Período 2001-2010). *Revista Colombia Amazónica* 5, 177–195.

828 Agudelo, E., Joven León, Á. V., Bonilla Castillo, C. A., Petreter Jr, M., Peláez, M., & Duponchelle, F.
829 (2013). Breeding, growth and exploitation of *Brachyplatystoma rousseauxii* in the Caqueta
830 River, Colombia. *Neotropical Ichthyology*, 11, 637-647. doi:[https://doi.org/10.1590/S1679-](https://doi.org/10.1590/S1679-62252013000300017)
831 [62252013000300017](https://doi.org/10.1590/S1679-62252013000300017)

832 Agudelo, E., Sánchez, C. L., Rodríguez, C. A., Bonilla-Castillo, C. A., & Gómez, G. A. (2011). Los
833 recursos pesqueros en la cuenca amazónica colombiana. Capítulo 5. In C. A. Lasso, F. d.
834 Paula Gutiérrez, M. A. Morales-Betancourt, E. Agudelo, H. Ramírez, & R. E. Ajiaco (Eds.),
835 *II. Diagnóstico de las pesquerías continentales de Colombia: cuencas del Magdalena-Cauca,*
836 *Sinú, Canalete, Atrato, Orinoco, Amazonas y vertiente del Pacífico. Serie Editorial Recursos*
837 *Hidrobiológicos y Pesqueros Continentales de Colombia.* (pp. 143-166). Bogotá, D. C.,
838 Colombia: Instituto de Investigación de los Recursos Biológicos Alexander von Humboldt
839 (IAvH).

840 Almeida, O. T., Lorenzen, K., & McGrath, D. G. (2009). Fishing agreements in the lower Amazon:
841 for gain and restraint. *Fisheries Management and Ecology*, 16, 61-67.

842 Almeida, R. M., Shi, Q., Gomes-Selman, J. M., Wu, X., Xue, Y., Angarita, H., . . . Flecker, A. S.
843 (2019). Reducing greenhouse gas emissions of Amazon hydropower with strategic dam

844 planning. *Nature Communications*, 10, 4281. doi:10.1038/s41467-019-12179-5

845 Alonso, J. C., & Pirker, L. E. M. (2005). Dinâmica populacional e estado actual da exploração de
846 piramutaba e de dourada In N. N. Fabr e & R. B. Barthem (Eds.), *O manejo da pesca dos*
847 *grandes bagres migradores: Piramutaba e dourada no eixo Solim es-Amazonas. Cole o*
848 *Documentos T cnicos: Estudos estrat gicos* (pp. 21-28). Manaus: IBAMA, ProV rzea.

849 Anderson, E. P., Jenkins, C. N., Heilpern, S., Maldonado-Ocampo, J. A., Carvajal-Vallejos, F. M.,
850 Encalada, A. C., . . . Tedesco, P. A. (2018). Fragmentation of Andes-to-Amazon connectivity
851 by hydropower dams. *Science Advance*, 4, eaao1642. doi:10.1126/sciadv.aao1642

852 Anderson, E. P., Montoya, M., Soto, A., Flores, H., & McClain, M. E. (2009). Challenges and
853 opportunities for co-management of a migratory fish, *Prochilodus nigricans*, in the Peruvian
854 Amazon. *American Fisheries Society Symposium*, 59, 741-756. doi:10.1111.613.4253

855 Anderson, E. P., Osborne, T., Maldonado-Ocampo, J. A., Mills-Novoa, M., Castello, L., Montoya,
856 M., . . . Jenkins, C. N. (2019). Energy development reveals blind spots for ecosystem
857 conservation in the Amazon Basin. *Frontiers in Ecology and the Environment* 19, 521-529.
858 doi:10.1002/fee.2114

859 Angelini, R., Fabr e, N. N., & da Silva-Jr., U. L. (2006). Trophic analysis and fishing simulation of
860 the biggest Amazonian catfish. *African Journal of Agricultural Research*, 1, 151-158.

861 Arantes, C. C., Fitzgerald, D. B., Hoeninghaus, D. J., & Winemiller, K. O. (2019). Impacts of
862 hydroelectric dams on fishes and fisheries in tropical rivers through the lens of functional
863 traits. *Current Opinion in Environmental Sustainability*, 37, 28-40.
864 doi:<https://doi.org/10.1016/j.cosust.2019.04.009>

865 Arantes, M. L., & Freitas, C. E. C. (2016). Effects of fisheries zoning and environmental
866 characteristics on population parameters of the tambaqui (*Colossoma macropomum*) in
867 managed floodplain lakes in the Central Amazon. *Fisheries Management & Ecology*, 23, 133-
868 143. doi:10.1111/fme.12164

869 Arantes, C. C., Winemiller, K. O., Asher, A., Castello, L., Hess, L. L., Petrere, M., & Freitas, C. E.
870 C. (2019). Floodplain land cover affects biomass distribution of fish functional diversity in
871 the Amazon River. *Scientific Reports*, 9, 16684. doi:10.1038/s41598-019-52243-0

872 Arantes, C. C., Winemiller, K. O., Petrere, M., Castello, L., Hess, L. L., & Freitas, C. E. C. (2018).
873 Relationships between forest cover and fish diversity in the Amazon River floodplain.
874 *Journal of Applied Ecology*, 55, 386-395. doi:10.1111/1365-2664.12967

875 Araujo-Lima, C. A. R. M., & Oliveira, E. C. (1998). Transport of larval fish in the Amazon. *Journal*
876 *of Fish Biology*, 53, 297-306.

877 Araujo-Lima, C. A. R. M., & Ruffino, M. L. (2003). Migratory fishes of the Brazilian Amazon. In J.
878 Carolsfeld, B. Harvey, C. Ross, & A. Baer (Eds.), *Migratory fishes of South America:*
879 *Biology, Fisheries and Conservation Status* (pp. 233-302). Washington, USA: IDRC, World
880 Bank.

881 Azevedo-Santos, V. M., Frederico, R. G., Fagundes, C. K., Pompeu, P. S., Pelicice, F. M., Padial, A.
882 A., . . . Henry, R. (2019). Protected areas: A focus on Brazilian freshwater biodiversity.
883 *Diversity and Distributions*, 25, 442-448. doi:10.1111/ddi.12871

884 Bailly, D., Agostinho, A. A., & Suzuki, H. I. (2008). Influence of the flood regime on the
885 reproduction of fish species with different reproductive strategies in the Cuiabá River, Upper
886 Pantanal, Brazil. *River Research and Applications*, 24, 1218-1229. doi:10.1002/rra.1147

887 Barthem, R., & Goulding, M. (1997). *The catfish connection. Ecology, migration and conservation of*
888 *Amazon predators*. New York: Columbia University Press.

889 Barthem, R., & Goulding, M. (2007). *Un ecosistema inesperado: la Amazonía revelada por la pesca*.
890 Lima, Peru: Museu Paraense Emilio Goeldi, Amazon Conservation Association (ACA).

891 Barthem, R. B., Goulding, M., Leite, R. G., Cañas, C., Forsberg, B., Venticinque, E., . . . Mercado, A.
892 (2017). Goliath catfish spawning in the far western Amazon confirmed by the distribution of
893 mature adults, drifting larvae and migrating juveniles. *Scientific Reports*, 7:41784.

894 doi:10.1038/srep41784

895 Barthem, R. B., Petrere., M. J., Isaac, V. J., Ribeiro, M. C. L. B., McGrath, D. G., Vieira, I. J. A., &
896 Valderama-Barco, M. (1997). The fisheries in the Amazon: problems and perspectives for its
897 management. In C. Valadares-Pádua & R. E. Bodmer (Eds.), *Conservation and management*
898 *of the wildlife in Brazil* (pp. 173-184). Brazil: MCTCNPq, Sociedade Civil Mimirauá.

899 Barthem, R. B., Silva-Júnior, U. L. d., Raseira, M. B., Goulding, M., & Venticinque, E. (2019). Bases
900 para a conservação e o manejo dos estoques pesqueiros da Amazônia. In A. V. Galucio & A.
901 L. d. C. Prudente (Eds.), *Museu Goeldi: 150 anos de ciência na Amazônia* (pp. 147-190).
902 Belém, Brasil: Editora MPEG.

903 Batista, V. S., Inhamuns, A. J., Freitas, C. E. C., & Freire-Brasil, D. (1998). Characterization of the
904 fishery in river communities in the low-Solimões/high-Amazon region. *Fisheries*
905 *Management and Ecology*, 5, 419-435. doi:10.1046/j.1365-2400.1998.550419.x

906 Bauer, S., & Hoyer, B. J. (2014). Migratory animals couple biodiversity and ecosystem functioning
907 worldwide. *Science*, 344, 1242552. doi:10.1126/science.1242552

908 Bayley, P. B. (1998). *Aquatic biodiversity and fisheries management in the Amazon*. Retrieved
909 from United Nations, World Bank, Washington, D.C.

910 Bayley, P. B., & Petrere, M. (1989). *Amazon Fisheries: Assessment methods, current status and*
911 *management options*. Paper presented at the Proceedings of the International Large River
912 Symposium, Honey Harbour, Ontario, Canada.

913 Berkeley, S. A., Chapman, C., & Sogard, S. M. (2004). Maternal age as a determinant of larval
914 growth and survival in a marine fish, *Sebastes melanops*. *Ecology*, 85, 1258-1264.
915 doi:doi:10.1890/03-0706

916 Birkeland, C., & Dayton, P. K. (2005). The importance in fishery management of leaving the big
917 ones. *Trends in Ecology & Evolution*, 20, 356-358.

918 Birnie-Gauvin, K., Franklin, P., Wilkes, M., & Aarestrup, K. (2019). Moving beyond fitting fish into

919 equations: Progressing the fish passage debate in the Anthropocene. *Aquatic Conservation:*
920 *Marine and Freshwater Ecosystems*, 29, 1095-1105. doi:10.1002/aqc.2946

921 Bonilla-Castillo, C. A., Agudelo, E. C., Gómez, G., & Duponchelle, F. (2018). Population dynamics
922 of *Prochilodus nigricans* (Characiformes: Prochilodontidae) in the Putumayo River.
923 *Neotropical Ichthyology*, 16, e170139. doi:https://doi.org/10.1590/1982-0224-20170139.

924 Borer, E. T., Seabloom, E. W., Shurin, J. B., Anderson, K. E., Blanchette, C. A., Broitman, B., . . .
925 Halpern, B. S. (2005). What determines the strength of a trophic cascade? *Ecology*, 86, 528-
926 537. doi:doi:10.1890/03-0816

927 Campos, C. P., Garcez, R. C. S., Catarino, M. F., Costa, G. A., & Freitas, C. E. C. (2015). Population
928 dynamics and stock assessment of *Colossoma macropomum* caught in the Manacapuru Lake
929 system (Amazon Basin, Brazil). *Fisheries Management and Ecology*, 22, 400-406.
930 doi:10.1111/fme.12139

931 Campos-Silva, J. V., & Peres, C. A. (2016). Community-based management induces rapid recovery
932 of a high-value tropical freshwater fishery. *Scientific Reports*, 6. doi:10.1038/srep34745

933 Campos-Silva, J. V., Hawes, J. E., & Peres, C. A. (2019). Population recovery, seasonal site fidelity,
934 and daily activity of pirarucu (*Arapaima* spp.) in an Amazonian floodplain mosaic.
935 *Freshwater Biology*, 64, 1255-1264. doi:10.1111/fwb.13301

936 Carolsfeld, J., Harvey, B., Ross, C., & Baer, A. (Eds.). (2003). *Migratory fishes of South America:*
937 *Biology, Fisheries and Conservation Status*. Washington, USA: IDRC, World Bank.

938 Carpenter, S. R., Stanley, E. H., & Zanden, M. J. V. (2011). State of the world's freshwater
939 ecosystems: physical, chemical, and biological changes. *Annual Review of Environment and*
940 *Resources*, 36, 75-99. doi:10.1146/annurev-environ-021810-094524

941 Casarim, R., Prado, I. G., Loures, R. C., & Pompeu, P. S. (2018). Fish movement patterns in a
942 Neotropical free-flowing tributary located downstream from a large dam. *Marine and*
943 *Freshwater Research*, 69, 1626-1634. doi:https://doi.org/10.1071/MF17216

- 944 Castello, L. (2008). Lateral migration of *Arapaima gigas* in floodplains of the Amazon. *Ecology of*
945 *Freshwater Fish*, 17, 38-46. doi:doi:10.1111/j.1600-0633.2007.00255.x
- 946 Castello, L., Bayley, P. B., Fabr e, N. N., & Batista, V. S. (2019). Flooding effects on abundance of an
947 exploited, long-lived fish population in river-floodplains of the Amazon. *Reviews in Fish*
948 *Biology and Fisheries*, 29, 487-500. doi:10.1007/s11160-019-09559-x
- 949 Castello, L., Hess, L. L., Thapa, R., McGrath, D. G., Arantes, C. C., Ren o, V. F., & Isaac, V. J.
950 (2018). Fishery yields vary with land cover on the Amazon River floodplain. *Fish and*
951 *Fisheries*, 19, 431-440. doi:doi:10.1111/faf.12261
- 952 Castello, L., Isaac, V. J., & Thapa, R. (2015). Flood pulse effects on multispecies fishery yields in the
953 Lower Amazon. *R Soc Open Sci*, 2. doi:10.1098/rsos.150299
- 954 Castello, L., & Macedo, M. N. (2016). Large-scale degradation of Amazonian freshwater ecosystems.
955 *Global Change Biology*, 22, 990-1007. doi:10.1111/gcb.13173
- 956 Castello, L., McGrath, D. G., Arantes, C. C., & Almeida, O. T. (2013). Accounting for heterogeneity
957 in small-scale fisheries management: The Amazon case. *Marine Policy*, 38, 557-565.
958 doi:http://dx.doi.org/10.1016/j.marpol.2012.09.001
- 959 Castello, L., McGrath, D. G., & Beck, P. S. A. (2011). Resource sustainability in small-scale fisheries
960 in the Lower Amazon floodplains *Fisheries Science*, 110, 356-364.
961 doi:doi:10.1016/j.fishres.2011.05.002
- 962 Castello, L., McGrath, D. G., Hess, L. L., Coe, M. T., Lef ebvre, P. A., Petry, P., . . . Arantes, C. C.
963 (2013). The vulnerability of Amazon freshwater ecosystems. *Conservation Letters*, 6, 217-
964 229. doi:10.1111/conl.12008
- 965 Castello, L., Stewart, D., & Arantes, C. (2011). Modeling population dynamics and conservation of
966 arapaima in the Amazon. *Reviews in Fish Biology and Fisheries*, 21, 623-640.
967 doi:10.1007/s11160-010-9197-z
- 968 Castello, L., & Stewart, D. J. (2010). Assessing CITES non-detriment findings procedures for

- 969 *Arapaima* in Brazil. *Journal of Applied Ichthyology*, 26, 49-56.
- 970 doi:<http://dx.doi.org/10.1111/j.1439-0426.2009.01355.x>
- 971 Catarino, M. F., Campos, C. P., Garcez, R. C. S., & Freitas, C. E. d. C. (2014). Population dynamics
972 of *Prochilodus nigricans* caught in Manacapuru Lake (Amazon basin, Brazil) *Boletim do*
973 *Instituto de Pesca*, 40, 589-595.
- 974 Cavole, L. M., Arantes, C. C., & Castello, L. (2015). How illegal are tropical small-scale fisheries?
975 An estimate for arapaima in the Amazon. *Fisheries Research*, 168, 1-5.
976 doi:<http://dx.doi.org/10.1016/j.fishres.2015.03.012>
- 977 Cheung, W. W. L., Sarmiento, J. L., Dunne, J., Frölicher, T. L., Lam, V. W. Y., Deng Palomares, M.
978 L., . . . Pauly, D. (2013). Shrinking of fishes exacerbates impacts of global ocean changes on
979 marine ecosystems. *Nature Climate Change*, 3, 254. doi:10.1038/nclimate1691
- 980 Coe, M. T., Costa, M. H., & Soares-Filho, B. S. (2009). The influence of historical and potential
981 future deforestation on the stream flow of the Amazon River – Land surface processes and
982 atmospheric feedbacks. *Journal of Hydrology*, 369, 165-174.
983 doi:<http://dx.doi.org/10.1016/j.jhydrol.2009.02.043>
- 984 Correa, S. B., Araujo, J. K., Penha, J. M. F., da Cunha, C. N., Stevenson, P. R., & Anderson, J. T.
985 (2015). Overfishing disrupts an ancient mutualism between frugivorous fishes and plants in
986 Neotropical wetlands. *Biological Conservation*, 191, 159-167.
987 <https://doi.org/10.1016/j.biocon.2015.06.019>
- 988 Correa, S. B., Costa-Pereira, R., Fleming, T., Goulding, M., & Anderson, J. T. (2015). Neotropical
989 fish–fruit interactions: eco-evolutionary dynamics and conservation. *Biological Reviews*, 90,
990 1263-1278. doi:10.1111/brv.12153
- 991 Correa, S. B., & Winemiller, K. (2018). Terrestrial–aquatic trophic linkages support fish production
992 in a tropical oligotrophic river. *Oecologia*, 186, 1069-1078. doi:10.1007/s00442-018-4093-7
- 993 Correa, S. B., Winemiller, K. O., López-Fernández, H., & Galetti, M. (2007). Evolutionary

994 perspectives on seed consumption and dispersal by fishes *BioScience*, 57, 748-756.
995 doi:10.1641/B570907

996 Corrêa, M. A. d. A., Kahn, J. R., & Freitas, C. E. d. C. (2014). Perverse incentives in fishery
997 management: The case of the defeso in the Brazilian Amazon. *Ecological Economics*, 106,
998 186-194. doi:http://dx.doi.org/10.1016/j.ecolecon.2014.07.023

999 Crampton, W. G. R., Castello, L., & Viana, J. P. (2004). Fisheries in the Amazon varzea: historical
1000 trends, current status, and factors affecting sustainability. In K. Silvius, R. E. Bodmer, & J. M.
1001 V. Fragoso (Eds.), *People in nature: wildlife conservation in South and Central America* (pp.
1002 76-95). New York: Columbia University Press.

1003 Cruz, R. E. A. (2020). *Pesca, economia e migração dos grandes bagres na Amazônia brasileira*.
1004 (PhD thesis), Universidade Federal do Pará, Belém, Brazil.

1005 de Merona, B., Juras, A. A., dos Santos, G. M., & Cintra, I. H. A. (2010). *Os peixes e a pesca no*
1006 *baixo Rio Tocantins: vinte anos depois da UHE Tucuruí*. Retrieved from Brasília:

1007 Diaz-Sarmiento, J. A., & Alvarez-León, R. (2003). Migratory Fishes of the Colombian Amazon. In J.
1008 Carolsfeld, B. Harvey, C. Ross, & A. Baer (Eds.), *Migratory fishes of South America:*
1009 *Biology, Fisheries and Conservation Status* (pp. 303-344). Washington, USA: IDRC, World
1010 Bank.

1011 Dingle, H., & Drake, V. A. (2007). What Is Migration? *BioScience*, 57, 113-121.
1012 doi:10.1641/b570206

1013 Dudgeon, D., Arthington, A. H., Gessner, M. O., Kawabata, Z.-I., Knowler, D. J., Lévêque, C., . . .
1014 Sullivan, C. A. (2006). Freshwater biodiversity: importance, threats, status and conservation
1015 challenges. *Biological Reviews*, 81, 163-182. doi:10.1017/S1464793105006950

1016 Duponchelle, F., Pouilly, M., Pécheyrán, C., Hauser, M., Renno, J.-F., Panfili, J., . . . Baras, E.
1017 (2016). Trans-Amazonian natal homing in giant catfish. *Journal of Applied Ecology*, 53,
1018 1511-1520. doi:10.1111/1365-2664.12665

- 1019 Estes, J. A., Terborgh, J., Brashares, J. S., Power, M. E., Berger, J., Bond, W. J., . . . Wardle, D. A.
1020 (2011). Trophic downgrading of planet Earth. *Science*, 333(6040), 301-306.
1021 doi:10.1126/science.1205106
- 1022 Fabré N. N., Barthem R. B., Carvalho A., & Angelini R. (2005). Sistema integrado para o manejo dos
1023 grandes bagres migradores. In: Fabré N. N. & R. B. Barthem (Eds.) O manejo da pesca dos
1024 grandes bagres migradores: Piramutaba e dourada no eixo Solimões-Amazonas. Coleção
1025 Documentos Técnicos: Estudos estratégicos. Manaus: IBAMA, ProVárzea, pp. 75–93
- 1026 Fausch, K. D., Torgersen, C. E., Baxter, C. V., & Li, H. W. (2002). Landscapes to riverscapes:
1027 bridging the gap between research and conservation of stream fishes: a continuous view of the
1028 river is needed to understand how processes interacting among scales set the context for
1029 stream fishes and their habitat. *BioScience*, 52, 483-498. doi:10.1641/0006-
1030 3568(2002)052[0483:ltrbtg]2.0.co;2
- 1031 Fernandes, C. C. (1997). Lateral migration of fishes in Amazon floodplains *Ecology of Freshwater*
1032 *Fish*, 6, 36-44. doi:10.1111/j.1600-0633.1997.tb00140.x
- 1033 Ferreira, C. S., Piedade, M. T. F., Wittmann, A. d. O., & Franco, A. C. (2010). Plant reproduction in
1034 the Central Amazonian floodplains: challenges and adaptations. *AoB Plants*, 2010.
1035 doi:10.1093/aobpla/plq009
- 1036 Ficke, A. D., Myrick, C. A., & Hansen, L. J. (2007). Potential impacts of global climate change on
1037 freshwater fisheries *Reviews in Fish Biology and Fisheries*, 17, 581-613. doi:10.1007/s11160-
1038 007-9059-5
- 1039 Filizola, N., & Guyot, J. L. (2009). Suspended sediment yields in the Amazon basin: an assessment
1040 using the Brazilian national data set. *Hydrological Processes*, 23, 3207-3215.
1041 doi:10.1002/hyp.7394
- 1042 Finer, M., & Jenkins, C. N. (2012). Proliferation of hydroelectric dams in the Andean Amazon and
1043 implications for Andes-Amazon connectivity. *PLoS One*, 7, e35126.

1044 doi:10.1371/journal.pone.0035126

1045 Flecker, A. S. (1996). Ecosystem engineering by a dominant detritivore in a diverse tropical stream.

1046 *Ecology*, 77, 1845-1854. doi:10.2307/2265788

1047 Fluet-Chouinard, E., Funge-Smith, S., & McIntyre, P. B. (2018). Global hidden harvest of freshwater

1048 fish revealed by household surveys. *Proceedings of the National Academy of Sciences*, 115,

1049 7623-7628. doi:10.1073/pnas.1721097115

1050 Forsberg, B. R., Melack, J. M., Dunne, T., Barthem, R. B., Goulding, M., Paiva, R. C. D., . . .

1051 Weisser, S. (2017). The potential impact of new Andean dams on Amazon fluvial ecosystems.

1052 *PLoS One*, 12, e0182254. doi:10.1371/journal.pone.0182254

1053 Frederico, R., Zuanon, J., & De Marco Júnior, P. (2018). Amazon protected areas and its ability to

1054 protect stream-dwelling fish fauna. *Biological Conservation*, 219, 12-19.

1055 doi:10.1016/j.biocon.2017.12.032

1056 Frederico, R. G., Olden, J. D., & Zuanon, J. (2016). Climate change sensitivity of threatened, and

1057 largely unprotected, Amazonian fishes. *Aquatic Conservation: Marine and Freshwater*

1058 *Ecosystems*, 26, 91-102. doi:10.1002/aqc.2658

1059 Freeman, M. C., Pringle, C. M., Greathouse, E. A., & Freeman, B. J. (2003). Ecosystem-level

1060 consequences of migratory faunal depletion caused by dams. In K. E. Limburg & J. R.

1061 Waldman (Eds.), *Biodiversity and Conservation of Shads Worldwide* (Vol. 35, pp. 255-266).

1062 Bethesda, Maryland: American Fisheries Society Symposium

1063 Freitas, C. E. C., Laurenson, L., Yamamoto, K. C., Forsberg, B. R., Petrere Jr., M., Arantes, C., &

1064 Siqueira-Souza, F. K. (2018). Fish species richness is associated with the availability of

1065 landscape components across seasons in the Amazonian floodplain. *PeerJ* 6:e5080.

1066 doi:10.7717/peerj.5080

1067 Freitas, C. E. C., Rivas, A. A. F., Campos, C. P., Sant'Anna, I., Kahn, J. R., Correa, M. A. A., &

1068 Catarino, M. F. (2012). The potential impacts of global climatic changes and dams on

- 1069 Amazonian fish and their fisheries. In H. Turker (Ed.), *New Advances and Contributions to*
1070 *Fish Biology* (pp. 175-195): Intech.
- 1071 Froese, R. (2004). Keep it simple: three indicators to deal with overfishing. *Fish and Fisheries*, 5, 86-
1072 91. doi:doi:10.1111/j.1467-2979.2004.00144.x
- 1073 Garcez, R. C. S., & Freitas, C. E. C. (2011). Seasonal catch distribution of tambaqui (*Colossoma*
1074 *macropomum*), Characidae in a central Amazon floodplain lake: implications for sustainable
1075 fisheries management. *Journal of Applied Ichthyology*, 27, 118-121. doi:10.1111/j.1439-
1076 0426.2010.01521.x
- 1077 García Vasquez, A., Alonso, J. C., Carvajal, F., Moreau, J., Nuñez, J., Renno, J. F., . . . Duponchelle,
1078 F. (2009). Life-history characteristics of the large Amazonian migratory catfish
1079 *Brachyplatystoma rousseauxii* in the Iquitos region, Peru. *Journal of Fish Biology*, 75, 2527-
1080 2551. doi:http://dx.doi.org/10.1111/j.1095-8649.2009.02444.x
- 1081 Garcia Vasquez, A., Tello, S., Vargas, G., & Duponchelle, F. (2009). Patterns of commercial fish
1082 landings in the Loreto region (Peruvian Amazon) between 1984 and 2006. *Fish Physiology*
1083 *and Biochemistry*, 35, 53-67. doi:http://dx.doi.org/10.1007/s10695-008-9212-7
- 1084 Garcia Vásquez, A., Vargas, G., Sánchez, H., Tello, S., & Duponchelle, F. (2015). Periodic life
1085 history strategy of *Psectrogaster rutiloides*, Kner 1858, in the Iquitos region, Peruvian
1086 Amazon. *Journal of Applied Ichthyology*, 31, 31-39. doi:10.1111/jai.12974
- 1087 Goulding, M. (1980). *The fishes and the forest. Explorations in Amazonian natural history*. Berkeley:
1088 University of California Press.
- 1089 Goulding, M., & Carvalho, M. (1982). Life history and management of the Tambaqui (*Colossoma*
1090 *macropomum* Characidae): an important amazonian food fish. *Revista Brasileira de*
1091 *Zoologia*, 30, 107-133.
- 1092 Goulding, M., Venticinque, E., Ribeiro, M. L. d. B., Barthem, R. B., Leite, R. G., Forsberg, B., . . .
1093 Cañas, C. (2019). Ecosystem-based management of Amazon fisheries and wetlands. *Fish and*

1094 *Fisheries*, 20, 138-158. doi:10.1111/faf.12328

1095 Hauser, M. (2018). *Migração dos grandes bagres Amazônicos pela perspectiva dos isótopos de*
1096 *Estrôncio em otólitos*. (PhD), Universidade Federal do Rondônia (UNIR), Porto Velho,
1097 Brazil.

1098 Hauser, M., Doria, C. R. C., Melo, L. R. C., Santos, A. R., Ayala, D. M., Nogueira, L. D., . . .
1099 Duponchelle, F. (2018). Age and growth of the Amazonian migratory catfish
1100 *Brachyplatystoma rousseauxii* in the Madeira River basin before the construction of dams.
1101 *Neotropical Ichthyology*, 16. doi:ARTN e17013010.1590/1982-0224-20170130

1102 Hauser, M., Doria, C. R. C., Santos, R. V., Garcia-Vasquez, A., Pouilly, M., Pecheyran, C., . . .
1103 Duponchelle, F. (2019). Shedding light on the migratory patterns of the Amazonian goliath
1104 catfish, *Brachyplatystoma platynemum*, using otolith $^{87}\text{Sr}:$ ^{86}Sr analyses. *Aquatic*
1105 *Conservation: Marine and Freshwater Ecosystems*, 29, 397-408. doi:10.1002/aqc.3046

1106 Hauser, M., Duponchelle, F., Hermann, T. W., Limburg, K. E., Castello, L., Stewart, D. J., . . . Doria,
1107 C. R. C. (2020). Unmasking continental natal homing in goliath catfish from the upper
1108 Amazon. *Freshwater Biology*, 65, 325-336. doi: <https://doi.org/10.1111/fwb.13427>

1109 Heithaus, M. R., Frid, A., Wirsing, A. J., & Worm, B. (2008). Predicting ecological consequences of
1110 marine top predator declines. *Trends in Ecology & Evolution*, 23, 202-210. doi:doi: DOI:
1111 10.1016/j.tree.2008.01.003

1112 Herrera-R, G.A., Oberdorff, T., Anderson, E.P., Brosse, S., Carvajal-Vallejos, F.M., Frederico, R.G.,
1113 Hidalgo, M., Jézéquel, C., Maldonado, M., Maldonado-Ocampo, J.A., Ortega, H., Radinger,
1114 J., Torrente-Vilara, G., Zuanon, J. & Tedesco, P.A. (in press). The combined effects of
1115 climate change and river fragmentation on the distribution of Andean Amazon fishes. *Global*
1116 *Change Biology*.

1117 Hoeninghaus, D. J., Winemiller, K. O., Layman, C. A., Arrington, D. A., & Jepsen, D. B. (2006).
1118 Effects of seasonality and migratory prey on body condition of *Cichla* species in a tropical

1119 floodplain river. *Ecology of Freshwater Fish*, 15, 398-407. doi:doi:10.1111/j.1600-

1120 0633.2006.00152.x

1121 Horn, M. H., Correa, S. B., Parolin, P., Pollux, B. J. A., Anderson, J. T., Lucas, C., . . . Goulding, M.

1122 (2011). Seed dispersal by fishes in tropical and temperate fresh waters: The growing

1123 evidence. *Acta Oecologica*, 37, 561-577. doi:http://dx.doi.org/10.1016/j.actao.2011.06.004

1124 Hurd, L. E., Sousa, R. G. C., Siqueira-Souza, F. K., Cooper, G. J., Kahn, J. R., & Freitas, C. E. C.

1125 (2016). Amazon floodplain fish communities: Habitat connectivity and conservation in a

1126 rapidly deteriorating environment. *Biological Conservation*, 195, 118-127.

1127 doi:http://dx.doi.org/10.1016/j.biocon.2016.01.005

1128 Isaac, V. J., & Almeida, M. C. (2011). *El consumo de pescado en la Amazonia brasileña.*

1129 *COPESCAALC Documento Ocasional. No. 13. FAO, Kingdom, WWF, IUCN and the Earth*

1130 *Institute at Columbia University.* Rome.

1131 Isaac, M. L., & Ruffino, V. J. (1996). Population dynamics of tambaqui, *Colossoma macropomum*

1132 Cuvier, in the Lower Amazon, Brazil. *Fisheries Management and Ecology*, 3, 315-333.

1133 doi:10.1046/j.1365-2400.1996.d01-154.x

1134 Isaac, V. J., Ruffino, M. L., & McGrath, D. G. (1998). *In search of a new approach to fisheries*

1135 *management in the middle Amazon region.* Paper presented at the Symposium on Fishery

1136 stock assessment models for the 21st century.

1137 Kahn, J. R., Freitas, C. E., & Petrere Jr., M. (2014). False shades of green: the case of Brazilian

1138 Amazonian hydropower. *Energies*, 7, 6063-6082. doi:10.3390/en7096063

1139 Jézéquel, C., Tedesco, P. A., Bigorne, R., Maldonado-Ocampo, J. A., Ortega, H., Hidalgo, M., . . .

1140 Oberdorff, T. (2020). A database of freshwater fish species of the Amazon Basin. *Scientific*

1141 *Data*, 7, 96. doi:10.1038/s41597-020-0436-4

1142 Junk, W. J., Bayley, P. B., & Sparks, J. S. (1989). *The flood pulse concept in river floodplain*

1143 *systems.* Paper presented at the International Large River Symposium.

- 1144 Latrubesse, E. M., Arima, E. Y., Dunne, T., Park, E., Baker, V. R., d’Horta, F. M., . . . Stevaux, J. C.
1145 (2017). Damming the rivers of the Amazon basin. *Nature*, 546, 363-369.
1146 doi:10.1038/nature22333
- 1147 Latrubesse, E. M., d’Horta, F. M., Ribas, C. C., Wittmann, F., Zuanon, J., Park, E., . . . Baker, P. A.
1148 (in press). Vulnerability of the biota in riverine and seasonally flooded habitats to damming of
1149 Amazonian rivers. *Aquatic Conservation: Marine and Freshwater Ecosystems*, n/a(n/a).
1150 doi:10.1002/aqc.3424
- 1151 Leal C. G., Lennox G. D., Ferraz S. F. B., Ferreira J., Gardner T. A., Thomson J. R., . . . Barlow J.
1152 (2020). Integrated terrestrial-freshwater planning doubles conservation of tropical aquatic
1153 species. Integrated terrestrial-freshwater planning doubles conservation of tropical aquatic
1154 species. *Science*, 370(6512), 117–121. <https://doi.org/10.1126/science.aba7580>
- 1155 Lees, A. C., Peres, C. A., Fearnside, P. M., Schneider, M., & Zuanon, J. A. S. (2016). Hydropower
1156 and the future of Amazonian biodiversity. *Biodiversity and Conservation*, 25, 451-466.
1157 doi:10.1007/s10531-016-1072-3
- 1158 Lennox, R. J., Paukert, C. P., Aarestrup, K., Auger-Méthé, M., Baumgartner, L., Birnie-Gauvin, K., .
1159 . . Cooke, S. J. (2019). One hundred pressing questions on the future of global fish migration
1160 science, conservation, and policy. *Frontiers in Ecology and Evolution*, 7.
1161 doi:10.3389/fevo.2019.00286
- 1162 Lima, A. C., & Araujo-Lima, C. A. R. M. (2004). The distributions of larval and juvenile fishes in
1163 Amazonian rivers of different nutrient status. *Freshwater Biology*, 49, 787-800.
1164 doi:10.1111/j.1365-2427.2004.01228.x
- 1165 Lima, M. A. L. (2017). *História do ecossistema e dos recursos pesqueiros frente a implementação de*
1166 *hidrelétricas na bacia do rio Madeira*. (PhD), Universidade Federal de Rondônia, Porto
1167 Velho, Brazil.
- 1168 Lira, N. A., Pompeu, P. S., Agostinho, C. S., Agostinho, A. A., Arcifa, M. S., & Pelicice, F. M.

1169 (2017). Fish passages in South America: an overview of studied facilities and research effort.
1170 *Neotropical Ichthyology*, 15, e160139. doi:<https://doi.org/10.1590/1982-0224-20160139>

1171 Lucas, M. C., & Baras, E. (2001). *Migration of Freshwater Fishes*. Oxford: Blackwell Science Ltd.

1172 Malhi, Y., Aragão, L. E. O. C., Galbraith, D., Huntingford, C., Fisher, R., Zelazowski, P., . . . Meir,
1173 P. (2009). Exploring the likelihood and mechanism of a climate-change-induced dieback of
1174 the Amazon rainforest. *Proceedings of the National Academy of Sciences*, 106, 20610-20615.
1175 doi:[10.1073/pnas.0804619106](https://doi.org/10.1073/pnas.0804619106)

1176 Malhi, Y., Roberts, J. T., Betts, R. A., Killeen, T. J., Li, W., & Nobre, C. A. (2008). Climate Change,
1177 Deforestation, and the Fate of the Amazon. *Science*, 319, 169-172.
1178 doi:[10.1126/science.1146961](https://doi.org/10.1126/science.1146961)

1179 Marques, H., Dias, J. H. P., Perbiche-Neves, G., Kashiwaqui, E. A. L., & Ramos, I. P. (2018).
1180 Importance of dam-free tributaries for conserving fish biodiversity in Neotropical reservoirs.
1181 *Biological Conservation*, 224, 347-354. doi:<https://doi.org/10.1016/j.biocon.2018.05.027>

1182 McClain, M. E., & Naiman, R. J. (2008). Andean Influences on the biogeochemistry and ecology of
1183 the Amazon River. *BioScience*, 58, 325-338. doi:<https://doi.org/10.1641/B580408>

1184 McIntyre, P. B., Reidy Liermann, C., Childress, E., Hamann, E., Hogan, D., Januchowski-Hartley, S.,
1185 . . . Pracheil, B. (2016). Conservation of migratory fishes in freshwater ecosystems. In G. P.
1186 Closs, M. Krkosek, & J. D. Olden (Eds.), *Conservation of Freshwater Fishes* (pp. 324-360).
1187 Cambridge: Cambridge University Press.

1188 Miranda-Chumacero, G., Álvarez, G., Luna, V., Wallace, R. B., & Painter, L. (2015). First
1189 observations on annual massive upstream migration of juvenile catfish *Trichomycterus* in an
1190 Amazonian River. *Environmental Biology of Fishes*, 98, 1913-1926. doi:[10.1007/s10641-015-](https://doi.org/10.1007/s10641-015-0407-3)
1191 [0407-3](https://doi.org/10.1007/s10641-015-0407-3)

1192 Monaghan, K. A., Agostinho, C. S., Pelicice, F. M., & Soares, A. M. V. M. (2020). The impact of a
1193 hydroelectric dam on Neotropical fish communities: A spatio-temporal analysis of the

1194 Trophic Upsurge Hypothesis. *Ecology of Freshwater Fish*, 29, 384-397.

1195 doi:10.1111/eff.12522

1196 Myers, B. J. E., Lynch, A. J., Bunnell, D. B., Chu, C., Falke, J. A., Kovach, R. P., . . . Paukert, C. P.

1197 (2017). Global synthesis of the documented and projected effects of climate change on inland

1198 fishes. *Reviews in Fish Biology and Fisheries*, 27, 339-361. doi:10.1007/s11160-017-9476-z

1199 Myers, R. A., Baum, J. K., Shepherd, T. D., Powers, S. P., & Peterson, C. H. (2007). Cascading

1200 Effects of the Loss of Apex Predatory Sharks from a Coastal Ocean. *Science*, 315, 1846-1850.

1201 Doi:10.1126/science.1138657

1202 Myers, R. A., & Mertz, G. (1998). The Limits of Exploitation: A Precautionary Approach.

1203 *Ecological Applications*, 8, S165-S169.

1204 Ortega, H., & Hidalgo, M. (2008). Freshwater fishes and aquatic habitats in Peru: Current knowledge

1205 and conservation. *Aquatic Ecosystem Health & Management*, 11, 257-271.

1206 doi:10.1080/14634980802319135

1207 Osorio, D., Terborgh, J., Alvarez, A., Ortega, H., Quispe, R., Chipollini, V., & Davenport, L. C.

1208 (2011). Lateral migration of fish between an oxbow lake and an Amazonian headwater river.

1209 *Ecology of Freshwater Fish*, 20, 619-627. doi:10.1111/j.1600-0633.2011.00511.x

1210 Pauly, D., Christensen, V., Dalsgaard, J., Froese, R., & Torres Jr., F. (1998). Fishing Down Marine

1211 Food Webs *Science*, 279, 860-863. doi:10.1126/science.279.5352.860

1212 Pelicice, F. M., Azevedo-Santos, V. M., Vitule, J. R. S., Orsi, M. L., Lima Junior, D. P., Magalhães,

1213 A. L. B., . . . Agostinho, A. A. (2017). Neotropical freshwater fishes imperilled by

1214 unsustainable policies. *Fish and Fisheries*, 18, 1119-1133. doi:10.1111/faf.12228

1215 Pelicice, F. M., Pompeu, P. S., & Agostinho, A. A. (2015). Large reservoirs as ecological barriers to

1216 downstream movements of Neotropical migratory fish. *Fish and Fisheries*, 16, 697-715.

1217 doi:10.1111/faf.12089

1218 Petrere, M., Barthem, R. B., Agudelo, E. A. C., & Gomez, B. C. (2004). Review of the large catfish

1219 fisheries in the upper Amazon and the stock depletion of piraiba (*Brachyplatystoma*
1220 *filamentosum* Lichtenstein). *Reviews in Fish Biology and Fisheries*, 14, 403-414.
1221 doi:10.1007/s11160-004-8362-7

1222 Pikitch, E. K., Santora, C., Babcock, E. A., Bakun, A., Bonfil, R., Conover, D. O., . . . Sainsbury, K.
1223 J. (2004). Ecosystem-Based Fishery Management. *Science*, 305, 346-347.
1224 doi:10.1126/science.1098222

1225 Pompeu, P. S., Agostinho, A. A., & Pelicice, F. M. (2012). Existing and Future Challenges: The
1226 Concept of Successful Fish Passage in South America. *River Research and Applications*, 28,
1227 504-512. doi:10.1002/rra.1557

1228 Pringle, C. M., Freeman, M. C., & Freeman, B. J. (2000). Regional Effects of Hydrologic Alterations
1229 on Riverine Macrobiota in the New World: Tropical-Temperate Comparisons. *BioScience*, 50,
1230 807-823. doi:10.1641/0006-3568(2000)050[0807:reohao]2.0.co;2

1231 Ribeiro, M. C. L. B., & Petrere, M. J. (1988). *Viagem de reconhecimento ao rio Tocantins e baixo rio*
1232 *Araguaia entre 20/11/88 e 8/12/88. Consultant Report* Retrieved from Brasilia (DF):

1233 Ribeiro, M. C. L. d. B., & Petrere, M. (1990). Fisheries ecology and management of the Jaraqui
1234 (Semaprochilodus Taeniurus, S. Insignis) in central Amazonia. *Regulated Rivers: Research &*
1235 *Management*, 5, 195-215. doi:10.1002/rrr.3450050302

1236 Ribeiro, M. C. L. d. B., Petrere Junior, M., & Juras, A. A. (1995). Ecological integrity and fisheries
1237 ecology of the Araguaia-Tocantins River Basin, Brazil. *Regulated Rivers: Research &*
1238 *Management*, 11, 325-350. doi:10.1002/rrr.3450110308

1239 Röpke, C. P., Amadio, S., Zuanon, J., Ferreira, E. J. G., Deus, C. P. d., Pires, T. H. S., & Winemiller,
1240 K. O. (2017). Simultaneous abrupt shifts in hydrology and fish assemblage structure in a
1241 floodplain lake in the central Amazon. *Scientific Reports*, 7, 40170. doi:10.1038/srep40170

1242 Röpke, C. P., Pires, T. H. S., Winemiller, K. O., de Fex Wolf, D., Deus, C. P., & Amadio, S. (2019).
1243 Reproductive allocation by Amazon fishes in relation to feeding strategy and hydrology.

- 1244 *Hydrobiologia*, 826, 291-305. doi:10.1007/s10750-018-3740-7
- 1245 Ruffino, M. L., & Isaac, V. J. (1999). Dinâmica populacional do surubim-tigre *Pseuplatystoma*
1246 *tigrinum* (Valenciennes, 1840) no médio Amazonas (Siluriformes, Pimelodidae). *Acta*
1247 *Amazonica*, 29, 463-476. doi:10.1590/1809-43921999293476
- 1248 Sant'Anna, I. R. A., Doria, C. R. C., & Freitas, C. E. C. (2014). Pre-impoundment stock assessment
1249 of two Pimelodidae species caught by small-scale fisheries in the Madeira River (Amazon
1250 Basin – Brazil). *Fisheries Management and Ecology*, 21, 322-329. doi:10.1111/fme.12082
- 1251 Santos, G. M. d. (1995). Impactos da hidroeletrica Samuel sobre as comunidades de peixes do rio
1252 Jamari (Rondônia, Brasil). *Acta Amazonica*, 25, 247-280. doi:
1253 <https://dx.doi.org/10.1590/1809-43921995253280>
- 1254 Santos, R. E., Pinto-Coelho, R. M., Fonseca, R., Simões, N. R., & Zanchi, F. B. (2018). The decline
1255 of fisheries on the Madeira River, Brazil: The high cost of the hydroelectric dams in the
1256 Amazon Basin. *Fisheries Management and Ecology*, 25, 380-391. doi:doi:10.1111/fme.12305
- 1257 Sheridan, J. A., & Bickford, D. (2011). Shrinking body size as an ecological response to climate
1258 change. *Nature Climate Change*, 1, 401. doi:10.1038/nclimate1259
- 1259 Silva, A. T., Lucas, M. C., Castro-Santos, T., Katopodis, C., Baumgartner, L. J., Thiem, J. D., . . .
1260 Cooke, S. J. (2018). The future of fish passage science, engineering, and practice. *Fish and*
1261 *Fisheries*, 19, 340-362. doi:10.1111/faf.12258
- 1262 Silva, E. A., & Stewart, D. J. (2017). Reproduction, feeding and migration patterns of *Prochilodus*
1263 *nigricans* (Characiformes: Prochilodontidae) in northeastern Ecuador. *Neotropical*
1264 *Ichthyology*, 15, e160171. doi:<https://doi.org/10.1590/1982-0224-20160171>
- 1265 Sorribas, M. V., Paiva, R. C. D., Melack, J. M., Bravo, J. M., Jones, C., Carvalho, L., . . . Costa, M.
1266 H. (2016). Projections of climate change effects on discharge and inundation in the Amazon
1267 basin. *Climatic Change*, 136, 555-570. doi:10.1007/s10584-016-1640-2
- 1268 Taylor, B. W., Flecker, A. S., & Hall, R. O. (2006). Loss of a harvested fish species disrupts carbon

1269 flow in a diverse tropical river. *Science*, 313, 833-836. doi:10.1126/science.1128223

1270 Uetanabaro, M., Wang, T., & Abe, A. S. (1993). Breeding behaviour of the red-bellied piranha,
 1271 *Pygocentrus nattereri*, in nature. *Environmental Biology of Fishes*, 38, 369-371.
 1272 doi:10.1007/BF00007529

1273 Van Damme, P. A., Carvajal-Vallejos, F., Camacho, J., Muñoz, H., & Coronel, J. S. (2011). Peces
 1274 migratorios de la Amazonía Boliviana. In P. A. Van Damme, F. Carvajal-Vallejos, & J.
 1275 Molina Carpio (Eds.), *Los peces y delfines de la Amazonía Boliviana - Hábitats,*
 1276 *potencialidades y amenazas* (pp. 149-200). Cochabamba, Bolivia: Editorial INIA.

1277 Van Damme, P. A., Córdova-Clavijo, L., Baigún, C., Hauser, M., Doria, C. R. d. C., & Duponchelle,
 1278 F. (2019). Upstream dam impacts on gilded catfish *Brachyplatystoma rousseauxii*
 1279 (Siluriformes: Pimelodidae) in the Bolivian Amazon. *Neotropical Ichthyology*, 17, e190118.
 1280 doi:http://dx.doi.org/10.1590/1982-0224-20190118

1281 Veríssimo, J. (1895). *A Pesca no Amazônia*. Rio de Janeiro: Livraria Clásica Alves and Companhia.

1282 Waddell J. C., Njeru S. M., Akhiyat Y. M., Schachner B. I., Correa-Roldán E. V., & Crampton W. G.
 1283 R. (2019). Reproductive life-history strategies in a species-rich assemblage of Amazonian
 1284 electric fishes. Reproductive life-history strategies in a species-rich assemblage of Amazonian
 1285 electric fishes. *PLoS One*, 14(12), e0226095. https://doi.org/10.1371/journal.pone.0226095.

1286 Welcomme, R. L. (1995). Relationships between fisheries and the integrity of river systems.
 1287 *Regulated Rivers: Research & Management*, 11, 121-136. doi:10.1002/rrr.3450110110

1288 Winemiller, K. O., & Jepsen, D. B. (1998). Effects of seasonality and fish movements on tropical
 1289 river food webs. *Journal of Fish Biology*, 53, 267-296. doi:10.1111/j.1095-
 1290 8649.1998.tb01032.x

1291 Winemiller, K. O., Marrero, C., & Taphorn, D. C. (1996). Perturbaciones causadas por el hombre a
 1292 las poblaciones de peces de los llanos y del piedemonte Andino de Venezuela. *Biollania*
 1293 *(Venezuela)*, 12, 13-48.

- 1294 Wootton, R. J. (1998). *The ecology of teleost fishes, Second Edition* (Vol. 24). Dordrecht, The
1295 Netherlands: Kluwer Academic Publisher.
- 1296 Wright, J. P., & Flecker, A. S. (2004). Deforesting the riverscape: the effects of wood on fish
1297 diversity in a Venezuelan piedmont stream. *Biological Conservation*, *120*, 443–451.
1298 doi:<https://doi.org/10.1016/j.biocon.2004.02.022>
- 1299 Xenopoulos, M. A., Lodge, D. M., Alcamo, J., Märker, M., Schulze, K., & Van Vuuren, D. P.
1300 (2005). Scenarios of freshwater fish extinctions from climate change and water withdrawal.
1301 *Global Change Biology*, *11*, 1557-1564. doi:10.1111/j.1365-2486.2005.001008.x
- 1302 Zed, Z., Wouter, B., Bastian, M., Claudia Véliz, R., Patrick, W., Waldo, L.-C., . . . William, S.
1303 (2016). Projected increases in the annual flood pulse of the Western Amazon. *Environmental*
1304 *Research Letters*, *11*, 014013. doi:10.1088/1748-9326/11/1/014013
- 1305 Ziv, G., Baran, E., Nam, S., Rodríguez-Iturbe, I., & Levin, S. A. (2012). Trading-off fish
1306 biodiversity, food security, and hydropower in the Mekong River Basin. *Proceedings of the*
1307 *National Academy of Sciences*, *109*, 5609-5614. doi:10.1073/pnas.1201423109
- 1308
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1311 **Tables & Figures**

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1313 **Table 1.** Relative contribution of the different categories of migratory fish species, per region,
 1314 to total fisheries landings in the Amazon basin, based on a total Amazonian landings of
 1315 173,000 tons.year⁻¹ and the percentage contribution of each region to these total landings
 1316 (Barthem & Goulding, 2007). LD: Long-Distance migratory species correspond to goliath
 1317 catfishes (*Brachyplatystoma* spp.); MDLS: Medium-Distance Large-sized Siluriformes
 1318 correspond to all other large migratory catfishes (*Pseudoplatystoma* spp., *Zungaro zungaro*,
 1319 *Phractocephalus hemiliopterus*, *Calophysus macropterus*, etc.); MDLC: Medium-Distance
 1320 Large-sized Characiformes correspond to *Colossoma macropomum* and *Piaractus*
 1321 *brachypomus*; MDS: Medium-Distance Small-sized correspond to most other smaller
 1322 Characiformes (*Prochilodus* spp., *Semaprochilodus* spp., *Brycon* spp., etc.); SD-R: Short-
 1323 Distance and Resident species (*Arapaima* spp., *Plagioscion squamosissimus*, most cichlid
 1324 species, etc.). For details about the data and methods, see Supplementary Table 2.

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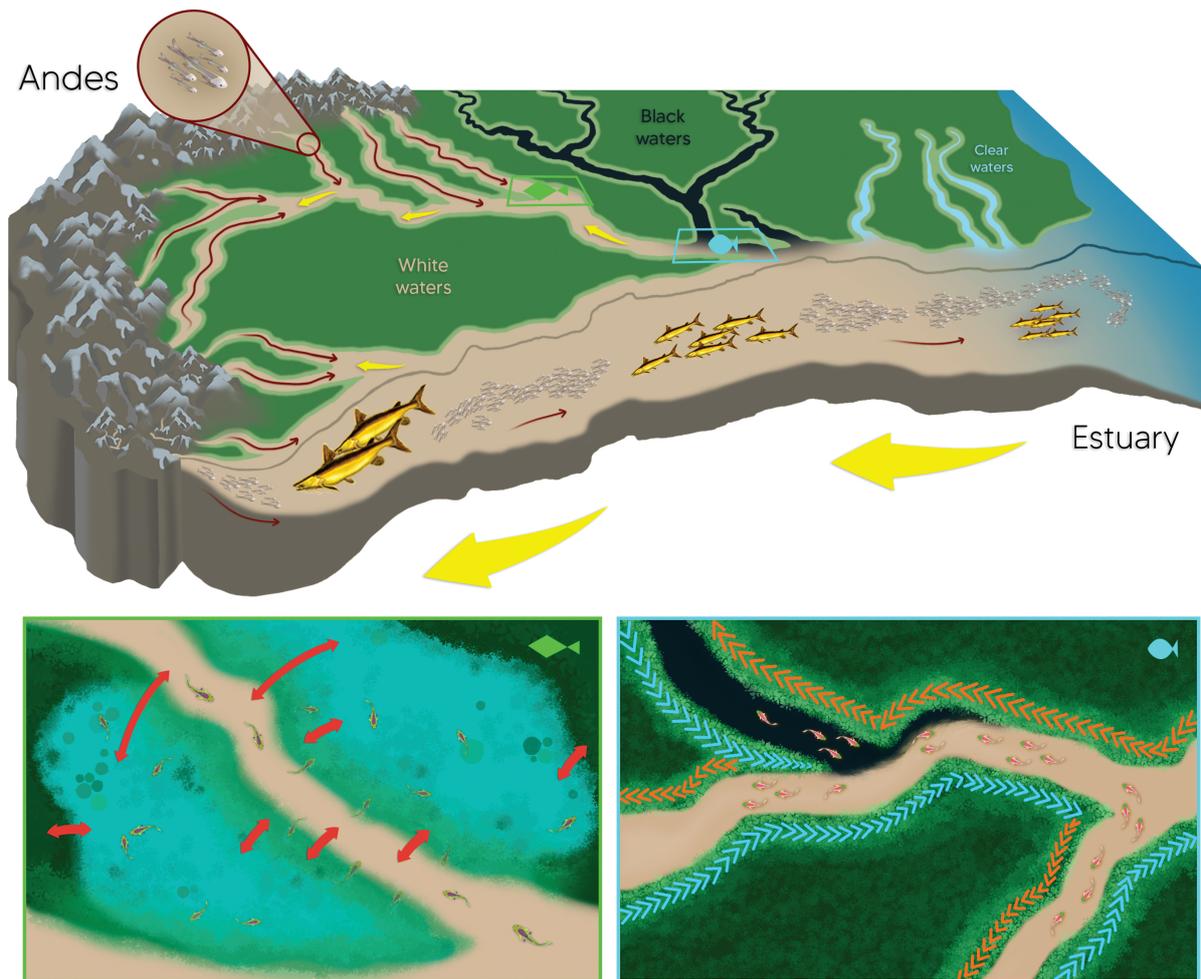
	% total landings	Mean landings	LD %	MDLS %	MDLC %	MDS %	SD-R %
Estuary (Belém)	28	48440	47	0.5	0.3	49.6	2.6
Lower Amazon	7	12110	22.3	7.9	5.5	61.7	2.6
Central Amazon (Manaus)	29	50170	9.9	12	5.1	70.2	2.8
Madeira	2	3460	9.9	6.7	2.0	72.6	8.8
Upper Madeira	2	3460	2.7	36.8	23.8	18.4	18.3
Purus-Juruá	4	6920	31.2	21.7	1.4	41.6	4.2
Border area Brasil, Colombia, Peru	7	12110	43.7	29.7	0.3	25.7	0.6
Peru	16	27680	2.3	6.2	1.6	85.4	4.5
Tocantins	5	8650	0	0	0	76.5	23.5

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1331 **Figure 1.** Illustration of the main fish migratory patterns in the Amazon basin (see text of
 1332 section “Diversity of migratory behaviours” for details). The main graph represents the long-
 1333 distance (several thousands kms) migrations of goliath catfishes, with larvae (brown loop)
 1334 drifting down (brown arrows) from their hatching areas in the white waters of the Andean
 1335 piedmont to their nursery areas in the Amazon estuary, where they will feed and grow a few
 1336 years before migrating back to their breeding areas in the Andean piedmont (large and slender
 1337 yellow arrows). The blue fish rectangle illustrates the medium distance (several hundred kms)
 1338 migrations, exemplified by the *Prochilodus* spp. and *Semaprochilodus* spp. upstream (orange
 1339 arrows) and downstream (blue arrows) movements between nutrient-poor black water and
 1340 nutrient-rich white water tributaries. The green fish rectangle illustrates the small distance (a
 1341 few kms) lateral migrations performed by most species between main rivers and their

1342 floodplains, comprising a wide array of both permanently (oxbow lakes) and temporarily
1343 flooded environments (forests and savannahs).

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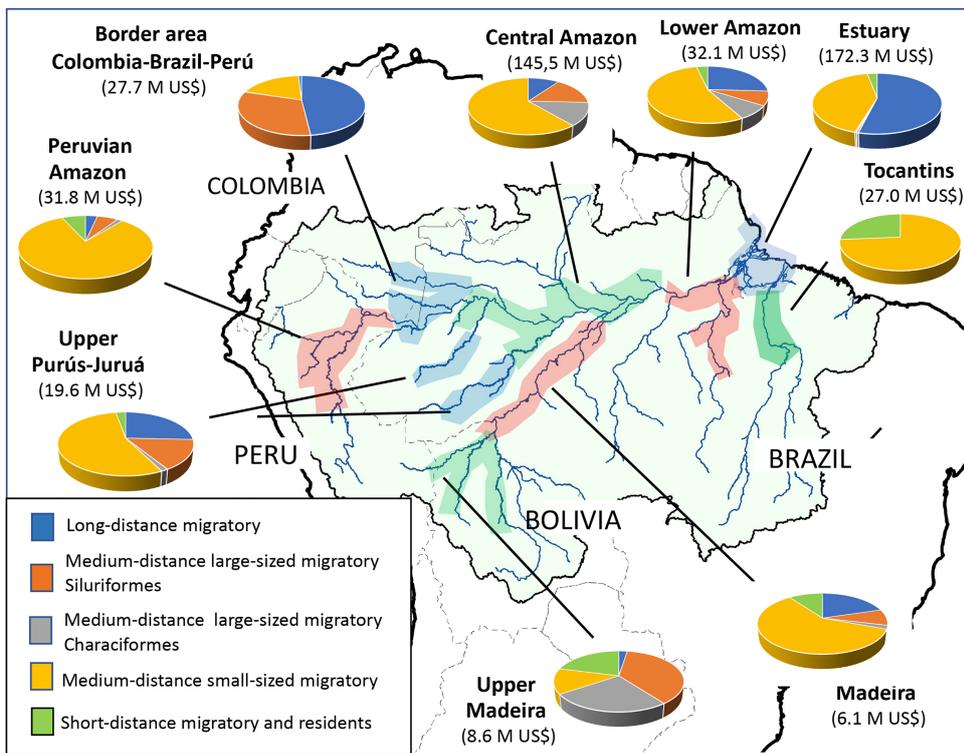
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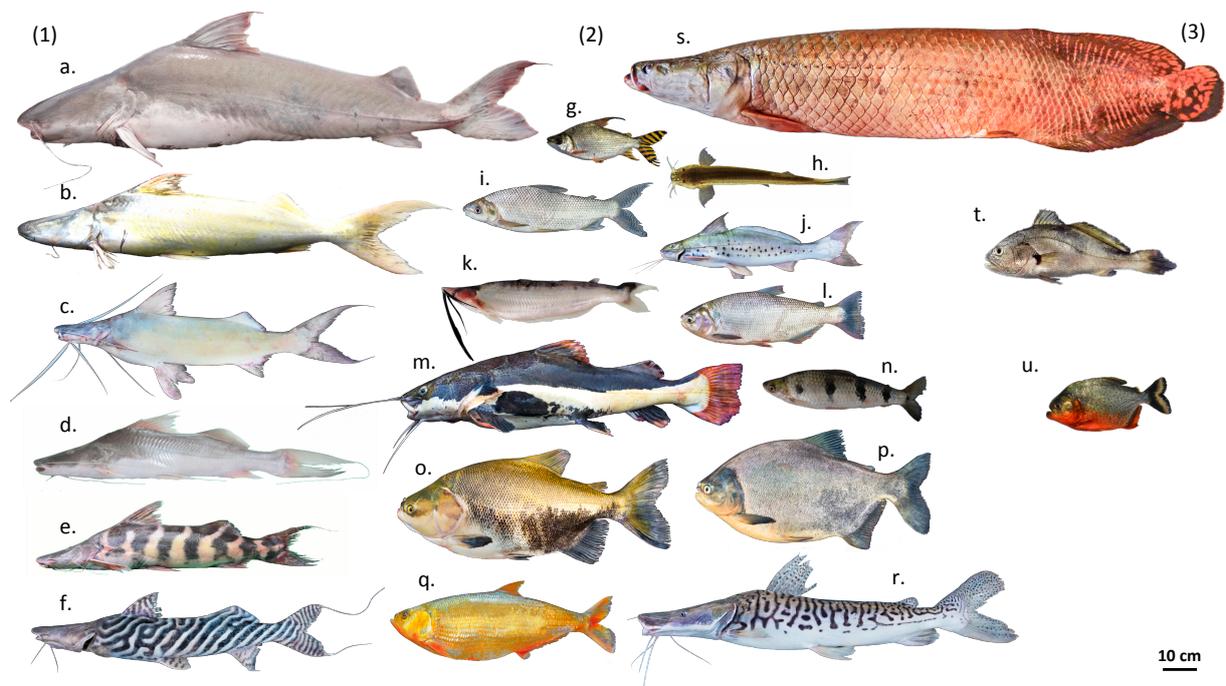
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1352 **Figure 2.** Relative economic contribution, per region, of the different categories of migratory
1353 fish species to total fisheries landings in the Amazon basin. Between brackets are the mean
1354 estimated economic contributions (in Million USD) of the region's landings. For details about
1355 the data and methods, see Supplementary Table 2.

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1359 **Figure 3.** Example of species belonging to the three main categories of migrations (most of
 1360 which are cited in the text):

1361 (1) Long-distance migrations: a. *Brachyplatystoma filamentosum*, b. *B. rousseauxii*, c. *B.*
 1362 *platynemum*, d. *B. vaillantii*, e. *B. juruense*, f. *B. tigrinum*.

1363 (2) Medium-distance migrations: g. *Semaprochilodus insignis*, h. *Trichomycterus barbouri*, i.
 1364 *Prochilodus nigricans*, j. *Calophysus macropterus*, k. *Hypophthalmus fimbriatus*, l. *Brycon*
 1365 *amazonicus*, m. *Phractocephalus hemiliopterus*, n. *Schizodon fasciatus*, o. *Colossoma*
 1366 *macropomum*, p. *Piaractus brachypomus*, q. *Pellona flavipinis*, r. *Pseudoplatystoma tigrinum*.

1367 (3) Short-distance migrations: s. *Arapaima* sp., t. *Plagioscion squamosissimus*, u.
 1368 *Pygocentrus nattereri*.

1369 For the sake of available space and visibility of small species, large species reaching over 1m
 1370 lengths (a, b, l, q, r, s) are not represented to their maximum length, unlike small and medium
 1371 species. The scale does not apply to *T. barbouri* (h), given its very small size at migration (~
 1372 30 mm).

1373 Photo credits: a,d,e: García Dávila et al. (2018); b: Fernando Carvajal-Vallejos;
1374 c,f,i,j,l,m,o,p,r: Aldo Echeverria; h: Guido Miranda (WCS); g,k,n,t-w: Arantes et al. (2019);
1375 q,s; Daniel Barroso.
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