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Fish passages in South America: an overview of studied facilities and research effort

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River regulation has fragmented fluvial ecosystems in South America, affecting fish migration and dispersion dynamics. In response, authorities have installed fish passage facilities (FPF) to mitigate impacts. However, little is known about the geographical distribution of these facilities, and no synthesis of the research effort applied to understanding their functioning and limitations exists. To address this issue, our study gathered the available scientific literature about fishways in South America to provide an overview of studied FPF and associated research effort. We found 80 studies that investigated 25 FPF, mostly ladders installed in the upper reaches of large rivers, particularly in the Paraná River Basin. One important finding is that most facilities do not lead to upstream and/or downstream sites due to the presence of other dams with no FPF. Though the number of studies has increased over the past 10 years, there is no consistent trend towards increased research effort. Overall, studies have focused on the fishway itself (*i.e.* upstream passage), and rarely evaluated broader issues (*i.e.* habitat distribution, population dynamics, conservation and management success). Our research therefore identified technical limitations of past studies, and revealed important gaps in the knowledge of FPF as a management tool.

Keywords: Conservation, Dam, Fishway, Impact, Management.

A implantação de barragens tem perturbado e fragmentado os ecossistemas fluviais da América do Sul, afetando a migração dos peixes e dinâmicas de dispersão. Sistemas de transposição de peixes (STPs) têm sido instalados na tentativa de atenuar esses impactos. No entanto, pouco se sabe sobre a distribuição geográfica desses dispositivos, bem como o esforço de pesquisa aplicado para entender seu funcionamento e limitações. Nosso trabalho reuniu a literatura disponível com a finalidade de fornecer um panorama sobre os mecanismos investigados na América do Sul, bem como revelar o esforço e perfil das pesquisas. Encontramos 80 estudos que investigaram 25 STPs, a maioria escadas instaladas nos trechos superiores de grandes rios, particularmente na bacia do rio Paraná. Um resultado interessante é que a maior parte dos STPs está desconectada de trechos a montante e jusante devido à presença de outras barragens sem STPs. Embora o número de estudos tenha aumentado na última década, não registramos tendência consistente de incremento ao longo dos anos. No geral, os estudos abordam aspectos do próprio STP, especificamente a passagem ascendente, ignorando temas mais abrangentes (*i.e.* distribuição de habitats, dinâmica populacional). Além disso, o foco da pesquisa se direciona especialmente às questões de eficiência da passagem e raramente ao contexto da conservação e sucesso do manejo. Nossa avaliação, portanto, indicou que os estudos pretéritos são tecnicamente limitados, revelando importantes lacunas sobre o conhecimento dos STPs como medida de manejo.

Palavras-chave: Barragens, Conservação, Gestão, Impacto, Passagens de peixes.

Introduction

River regulation has significantly disrupted fluvial ecosystems in South America (Agostinho *et al*., 2016). This process caused severe changes in the natural flow regime and habitat availability, with implications for the abundance of aquatic organisms and community structure. Migratory fishes are particularly affected by river damming, because dams and large impoundments interrupt migration routes (Agostinho *et al*., 2007a; Antonio *et al*., 2007; Pelicice *et al*., 2015) and cause the loss of spawning sites and nursery areas (Pelicice, Agostinho, 2008). The current decline of migratory fishes, which include local extinctions, has been linked to disturbances caused by river damming (Freeman *et al*., 2003; Okada *et al*., 2005; Hoeinghaus *et al*., 2009; Agostinho *et al*., 2016).

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Management actions have been proposed to mitigate these impacts. Among these initiatives, fish passage facilities (hereafter FPF) have been installed in different South American basins. Designed to reconnect river segments fragmented by dams, FPF allow, in principle, the continuity of spawning migrations by helping fish to overcome the dam (Clay, 1995). This approach was originally developed in Europe and North America, where fish ladders had relatively high success enabling the upstream migration of salmon species (Agostinho *et al*., 2007a). In South America, particularly in Brazil, the first FPF was installed in the beginning of the 20th century; these devices, however, became popular in the past 50 years, when different types were installed in many basins, including lifts, locks, artificial canals and ladders (Agostinho *et al*., 2002; Godinho, Kynard, 2008). These facilities are usually seen as efficient management actions, and received support from authorities, stakeholders and the general public. Recent studies, however, have elicited discussions about the value of FPF to foster migratory fish conservation in South America, because several aspects concerning their functioning and management role remain poorly known (*e.g*., Agostinho *et al*., 2002; Oldani *et al*., 2007; Pelicice, Agostinho, 2008; Pompeu *et al*., 2012; Pelicice *et al*., 2015). These studies argue that evaluations rarely preceeded or followed the construction of FPF, while monitoring programs traditionally focused on variables with partial relevance for conservation plans (*e.g*., upstream passage), while neglecting other important issues (*e.g*., population dynamics, spawning, recruitment and dispersion). Not surprisingly, important limitations have been reported, as for example, high selectivity for upstream (*e.g*., Agostinho *et al*., 2007c; Volpato *et al*., 2009) and downstream passage (*e.g*., Agostinho *et al*., 2007b; Agostinho *et al*., 2011; Suzuki *et al*., 2011; Pelicice, Agostinho, 2012; Britto, Carvalho, 2013). These limitations cannot be ignored, since they compromise the primary function of FPF (*i.e*., reestablishment of migratory movements) and may promote changes in the structure and distribution of populations at the regional level, causing additional impacts (Pelicice, Agostinho, 2008). In summary, the common assertion that FPF are efficient management tools has been challenged by studies conducted in South America (cited above) and elsewhere (McLaughlin *et al*., 2012; Brown *et al*., 2013; Kemp, 2016).

In this context, systematic analysis and review of the scientific literature devoted to FPF is needed to reveal patterns and trends in research effort, main questions and methodologies (*e.g*., Roscoe, Hinch, 2010). Yet, no such study has focused on South America. This information is important because recent studies (*e.g*., Pelicice, Agostinho, 2008; Pompeu *et al*., 2012) have cast doubt on the conservation value of FPF and highlighted the need to increase research effort applied to this topic. In addition, a comprehensive review can reveal knowledge gaps, improve our understanding of management success, and guide future research. For example, we know little about the number and spatial distribution of studied FPF across South America; similarly, we do not know how research effort (number and type of studies) is distributed among existing FPF. It has been suggested, for example, that most studies focus on upstream migration and neglect post-passage survival and conservation issues (*e.g*., Pompeu *et al*., 2012; Pelicice *et al*., 2015). A systematic literature review would provide valuable information regarding these topics. To fill that need, this study aimed to characterize studied FPF in South America, and systematically review the evidence in studies that investigated these structures. In particular, we provide an overview of studied FPF (geographical distribution, types and spatial scenarios) and describe their research effort and profile (number of studies, study type, questions and other issues).

Material and Methods

Data collection. Our study is based on past scientific research on FPF installed in South America. We conducted an extensive literature search by combining different keywords (fish, dam, fishway, passage, ladder, lift, lateral canal; in Portuguese and English) in several databases, *i.e*., Web of Science (www.isiknowledge.com), Scielo (www.scielo.org), Portal Capes (www.periodicos.capes.gov.br) and Google® (www.google.com.br). In addition, we complemented our survey by consulting experts in the field, personal libraries, and cross-reference search. We targeted peer-review articles published in scientific journals, but we complemented the search with theses, dissertations, book chapters and conference abstracts (including all expanded abstracts published in the proceedings of the International Symposium on Fish Passages in South America, held in Brazil in 2007 and 2012). Among the types of FPF considered were ladders, lifts, lateral canals, locks and trap-truck systems (*sensu* Agostinho *et al.*, 2007a).

Fish passage overview. From each independent study, we collected information about the dam and the fish passage. Concerning the dam, we recorded the name, location, river and basin; concerning the FPF, we recorded the name, type (ladder, lift, lateral canal, lock and trap-truck), hydraulic model (for ladders) and spatial characteristics. We classified each FPF according to: (i) river type, *i.e*., main channel (when installed in the main stem), main tributary (when installed in tributaries that flow into the main stem, *e.g*., Grande, Paranapanema and Uruguay rivers) and secondary tributary (other rivers); (ii) location in the basin, *i.e*., upper, middle and lower reaches; and (iii) connectivity to upstream and downstream reaches, *i.e*., relative to the presence of other dams and FPF.

Research effort and profile. From each independent study, we recorded year of publication and year in which the study was conducted. To describe the research profile of each study, we collected information about study type, sampling location, passage direction, level of biotic organization and target taxon. We sorted studies into six study type categories: sampling, experiment, mark-recapture, modelling (*i.e.* predictive approaches), telemetry and review/synthesis. Sampling locations were also classified in three categories: those that sampled only upstream and/or downstream from the dam (surrounding), those that sampled only the FPF themselves (FPF) and those that sampled both (surrounding+FPF). Research focus on passage direction (upstream and/or downstream) was classified as upstream, downstream and upstream+downstream. The level of biotic organization addressed by each study was categorized as population (when it focused on a single species), multi-species (when it focused on several populations) or assemblage (when it considered all species). Target species from population-level studies were recorded and classified as Migratory and Non-migratory (*sensu* Agostinho *et al*., 2003).

We also identified the general research question of each study, following methodology proposed by Roscoe, Hinch (2010). Research questions were classified as: (i) efficiency, when it examined overall aspects (quantitative and qualitative) of fish passage at the FPF; (ii) mechanism, when the study addressed factors that affect fish passage (*e.g.*, environmental, structural/hydraulic and/or behavioral); (iii) physiology, when the study considered endogenous or physiological consequences of the passage (*e.g.*, energetic costs, metabolism); and (iv) consequences, when the study addressed post-passage effects other than physiological responses (*e.g.*, reproduction success, predation, mortality, injuries).

Data analysis. To provide an overview of studied FPF in South America, we inventoried the total number of recorded facilities, calculated the percentage falling into each type, and plotted these facilities on a map. In order to investigate spatial questions, we calculated the percentage of facilities installed in each river type (main channel, main tributary or secondary tributary), location type (upper, middle and lower) and connectivity category.

To investigate research effort, we calculated the number of papers published each year, and the time interval between the beginning of the FPF operation and the date of first evaluation. To do this, we calculated the average, minimum and maximum time interval, and grouped the studies in the following classes: 0, 1-3, 4-6, 7-9 and > 10 years. The relationship between FPF age and the time elapsed before the first evaluation was tested through nonparametric Spearman Rank correlation (5% significance level). We also calculated the percentage of studies in each spatial scenario and research profile category, and listed all target-species (with their frequency of occurrence) investigated by population-level studies. Finally, concerning passage direction, we calculated the ratio between the number of studies focusing on downstream and upstream passage (downstream:upstream).

To determine the relative prevalence of research questions among studies, we calculated the percentage of studies in each category (efficiency, mechanism, physiology and consequence), and calculated their number in each year (1984-2014).

Results

Fish passage overview. According to our investigation, 25 FPF have been studied in different river basins in South America (Tab. 1), located mainly in the Paraná (52%) and Amazon (12%) basins (Fig. 1). Most are ladders (70.8%), followed by lifts (8.3%), lateral canals (8.3%), trap-truck systems (8.3%) and locks (4.2%).

Tab. 1. Fish passage facilities in South America based on studies retrieved in our literature survey. N = number of studies. Review/synthesis and modelling papers are not listed in the table. Review/Synthesis papers: Agostinho *et al*. (2002); Agostinho *et al*. (2004); Baigún *et al*. (2007); Godinho, Kynard (2008); Lopes, Silva (2012); Pompeu *et al*. (2012); Pelicice *et al*. (2015). Modelling papers: Duarte *et al*. (2012); Santos *et al*. (2007); Santos, Martinez (2012); Santos *et al*. (2012).

Fish passage	Type	Type (ladder)	Dam	River	Basin	N	Studies
1) Santo Antônio	Lateral Canal		Santo Antônio	Madeira	Amazon	1	Rodrigues *et al.* (2012)
2) Lajeado	Ladder	Weir and Orifice	Lajeado	Tocantins	Amazon	5	Agostinho *et al.* (2007c); Agostinho *et al.* (2007b); Agostinho *et al.* (2007d); Agostinho *et al.* (2011); Agostinho *et al.* (2012)
3) Peixe Angical	Ladder	Weir and Orifice	Peixe Angical	Tocantins	Amazon	6	Agostinho *et al.* (2009); Freitas *et al.* (2009); Pereira-Assis *et al.* (2009a); Pereira-Assis *et al.* (2009b); Pereira-Assis (2010); Pelicice, Agostinho (2012)
4) Igarapé	Ladder		Igarapé	Paraopeba	São Francisco	2	Alves (2007a); Alves (2012)

Tab. 1. (continued)

Fish passage	Type	Type (ladder)	Dam	River	Basin	N	Studies
5) Santa Clara	Lift (trap) and truck		Santa Clara	Mucuri	Mucuri	5	Pompeu *et al*. (2004); Pompeu, Martinez (2005); Pompeu, Martinez (2006); Pompeu, Martinez (2007); Pompeu *et al*. (2011)
6) Risoleta Neves	Ladder (trap) and truck	Pool & weir	Risoleta Neves	Doce	Doce	1	Braga *et al*. (2007)
7) Baguari	Ladder	Vertical-slot	Baguari	Doce	Doce	1	Silva *et al*. (2012a)
8) Ilha dos Pombos	Ladder		Ilha dos Pombos	Paraíba do Sul	Paraíba do Sul	1	Bastos *et al*. (2009)
9) Funil	Lift		Funil	Grande	Paraná	6	Alves *et al*. (2007b); Godinho *et al*. (2007); Pereira, Pompeu (2012); Souza *et al*. (2007); Suzuki *et al*. (2011); Suzuki *et al*. (2013)
10) Igarapava	Ladder	Vertical-slot	Igarapava	Grande	Paraná	8	Bizzoto *et al*. (2009); Bowen *et al*. (2006); Casali *et al*.(2009); Godinho *et al*. (2012); Maia *et al*. (2007); Silva *et al*. (2012b); Vono (2004); Vono *et al*. (2007)
11) Canoas I	Ladder	Weir and Orifice	Canoas I	Paranapanema	Paraná	4	Britto, Carvalho (2013); Lopes *et al*. (2007); Pelicice, Agostinho (2008); Ramos *et al*. (2012)
12) Canoas II	Ladder	Weir and Orifice	Canoas II	Paranapanema	Paraná	4	Britto, Carvalho (2013); Lopes *et al*. (2007); Pelicice, Agostinho (2008); Ramos *et al*. (2012)
13) Ourinhos	Ladder	Pool &Weir	Ourinhos	Paranapanema	Paraná	1	Arcifa, Esguícero (2012)
14) Cachoeira das Emas	Ladder	Pool &Weir	Cachoeira das Emas	Mogi Guassu	Paraná	1	Godoy (1987)
15) Gavião Peixoto	Ladder		Gavião Peixoto	Jacaré-Guaçu	Paraná	1	Esguícero, Arcifa (2010)
16) Palmeiras	Ladder	Weir and Orifice	Palmeiras	Sapucaí-Mirim	Paraná	1	Souza *et al*. (2012)
17) Salto de Morais	Ladder		Salto de Morais	Tijuco	Paraná	1	Godinho *et al*. (1991)
18) Porto-Primavera	Ladder	Weir and Orifice	Porto Primavera	Paraná	Paraná	9	Antonio *et al*. (2007); Assumpção *et al*. (2012); Makrakis *et al*. (2007a); Makrakis *et al*. (2007b); Makrakis *et al*. (2012); Pelicice, Agostinho (2008); Silva *et al*. (2012c); Volpato *et al*. (2009); Wagner *et al*. (2012)
19) Canal da Piracema	Lateral Canal		Itaipu	Paraná	Paraná	6	Fontes-Júnior *et al*. (2012a); Fontes-Júnior *et al*. (2012b); Hahn *et al*. (2007); Hahn (2007); Makrakis *et al*. (2007c); Makrakis *et al*. (2010)
20) Escada de Itaipu	Ladder	Weir and Orifice	Itaipu	Paraná	Paraná	4	Borguethi *et al*. (1994); Fernandez *et al*. (2004); Fernandez *et al*. (2007a); Fernandez *et al*. (2007b)
21) Yacyreta	Lift		Yacyretá	Paraná	Paraná	3	Oldani *et al*. (2001); Oldani, Baigún (2002); Oldani *et al*. (2007)
22) Salto Grande	Lock		Salto Grande	Uruguay	Uruguay	1	Oldani *et al*. (2007)
23) ETA III Ribeirão Garcia	Ladder		ETA III	Itajaí-Açú	Itajaí	1	Moretto (2005)
24) José Barasuol	Lateral Canal		José Barasuol	Ijuí	Uruguay	1	Kusma, Ferreira (2009)
25) Rota 28	Ladder	Pool &Weir	Rota 28	Pilcomayo	Pilcomayo	1	Baigún *et al*. (2012)

Fig. 1. Spatial distribution of fish passage facilities in South America whose function has been investigated. Identification numbers and respective studies are shown in Tab. 1.

Most FPF were installed in large rivers (44% in the main channel and 36% in main tributaries) (Fig. 2a), and in upper reaches of the basin (Fig. 2b). We recorded eight different connectivity scenarios (Fig. 3). All studied FPF were located upstream or downstream of another dam, and 59.1% had dams in both directions. Upstream dams were present in 86.4% of the cases, being 31.8% equipped with FPF; downstream dams were present in 72.7% of the cases, being 40.9% equipped with FPF (Fig. 3). Some studied FPF are isolated in both directions (18.2%), while some are connected (free stretch or via FPF) to both upstream and downstream reaches (31.6%).

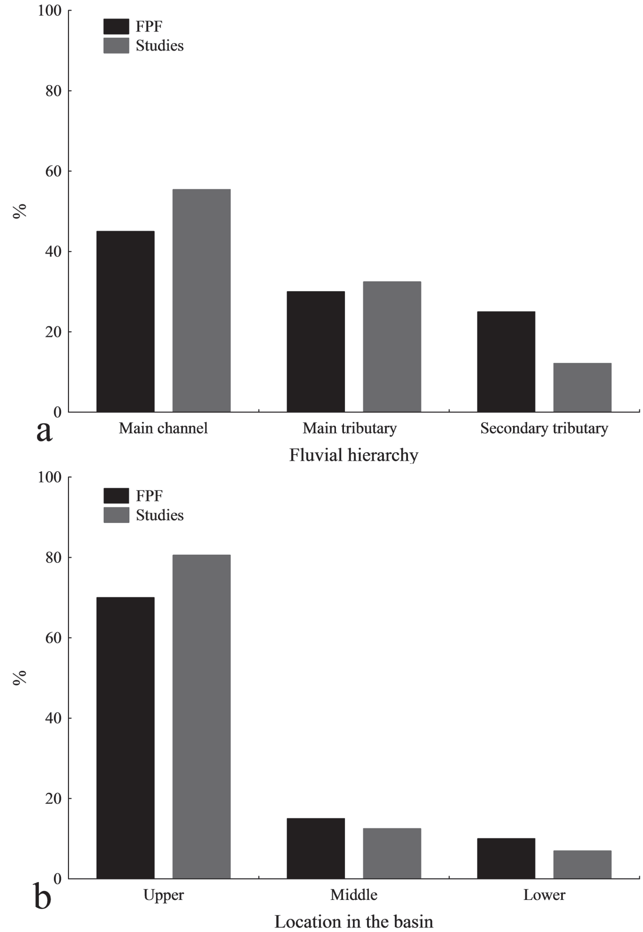

Fig. 2. Proportion of fish passage facilities (FPF) and studies in the different categories of river type and location in the basin. **a.** fluvial hierarchy; **b.** location in the basin.

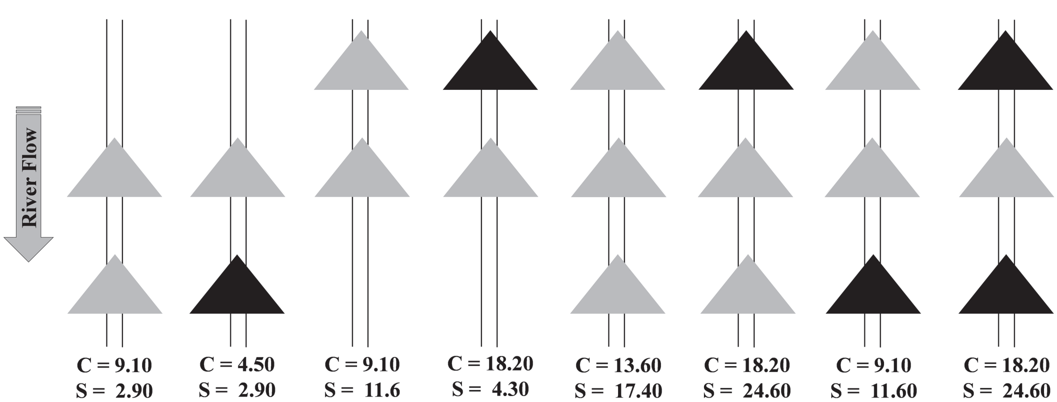

Fig. 3. Connectivity of the studied dam (middle triangle) with upstream and downstream reaches, mediated by the presence/absence of other dams (other triangles) and fish passage facilities (black = passage absent; grey = passage present). The figure shows the percentage of each connectivity scenario (C) and studies (S).

Research effort and profile. Our literature search retrieved 80 independent studies, including peer-reviewed articles (70%), abstracts (15%), book chapters (11.2%), theses, dissertations and monographs (3.8%). We recorded relatively few studies published in any given year, with almost all studies published in the last decade, especially in 2007 and 2012, which are the dates of the International Symposia on Fish Passages in South America (Fig. 4). Most studies investigated ladders (68.9%), while the remaining focused on lifts (12.2%), lateral canals (9.5%), trap-truck systems (8.1%) and locks (1.4%). Passage facilities located in the Paraná and Tocantins river basins had more research effort, with 49 and 11 publications, respectively (Tab. 1).

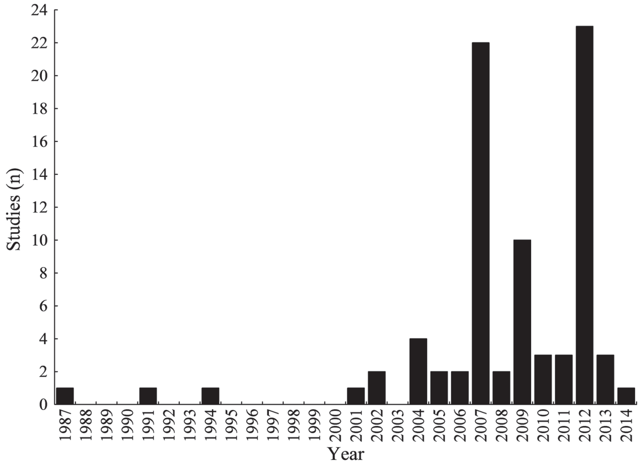

Fig. 4. Number of studies published over the years (1987-2014) that investigated fish passage facilities in South America.

Most studies focused on FPF installed in the main channel and main tributaries (Fig. 2a); virtually all studies were carried out in upper reaches (Fig. 2b). Concerning connectivity, most studies (78.2%) focused on FPF located between upstream and downstream dams (Fig. 3). A total of 68% of studies investigated FPF that were disconnected from downstream (39.1%) or upstream reaches (53.5%); only 31.9% focused on FPF that were connected (by freely flowing stretches of river or via FPF) to both upstream and downstream reaches (Fig. 3).

Our data indicated that once some FPF started operating, their first evaluation was delayed (Fig. 5). The mean time interval to the first evaluation was 3.32 years (range: 0 to 34 years), and most FPF (69%) were studied within 3 years of operation. The age of facilities correlated negatively with the number of years elapsed before the first evaluation (Spearman: $t = -2.91$; $R = 0.37$, $p = 0.0052$), indicating that evaluation of older FPF has been delayed.

Most studies were based on sampling (55.7%), followed by telemetry (12.4%), mark/recapture (10.2%), experiments (10.2%), review/synthesis (9.4%) and modelling (2%) (Fig. 6a). Investigations usually focused on the FPF themselves, but some studies included sites surrounding the dam (Fig. 6b). One important finding is that upstream passage received greater research effort than downstream passage (Fig. 6c); for each study assessing downstream passage, eight focused on upstream passage (1:8 ratio). Most studies focused on fish assemblages (Fig. 6d), and population-level studies investigated 60 different species, of which 42% were migratory and 58% non-migratory. Migratory fishes were more frequently investigated than non-migratory fishes, especially *Prochilodus lineatus*, *Pimelodus maculatus*, *Salminus brasiliensis*, *Megaeporinus elongatus* and *Piaractus mesopotamicus* (Tab. 2). Among non-migratory species, frequent target-species were *Leporinus friderici*, *Hypostomus* sp., *Schizodon borellii* and *Schizodon nasutus*. Across all studies, *P. lineatus* and *P. maculatus* were the most frequently investigated species (Tab. 2).

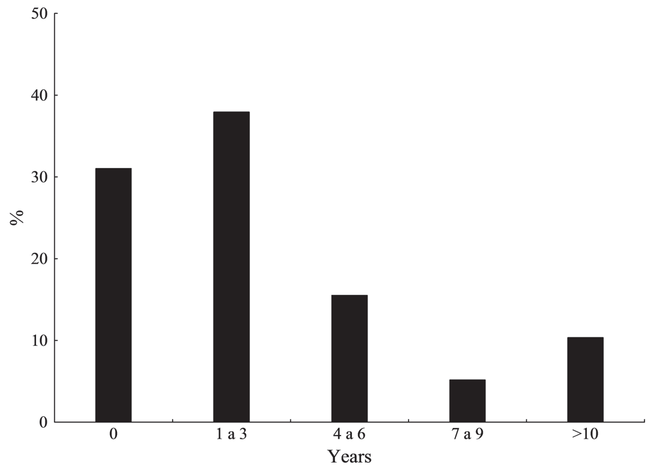

Fig. 5. Time interval (classes) between the beginning of operation of the fish passage and its first evaluation.

Studies addressed mainly questions of efficiency (62%), followed by consequence (20 %) and mechanism (16%); very few studies (2%) focused on physiology (Fig. 7a). Efficiency questions were consistently frequent over the years, while questions about mechanism were investigated sporadically, especially in years of high scientific production associated with the two symposia (Fig. 7b). Questions of consequence and physiology remained few in number in all years.

Discussion

Our study provided quantitative evidence that FPF in South America have received substantial research attention, since our investigation retrieved 80 independent studies. This effort, however, was unevenly distributed over time. Even though FPF have been constructed since the beginning of the 20th century (Agostinho *et al*., 2007a), most studies occurred in the last decade (2004-2014). Relatively few articles were published each year, and there was no temporal trend of increase or decrease. In addition, research effort appears to be unbalanced, since it was restricted to relatively

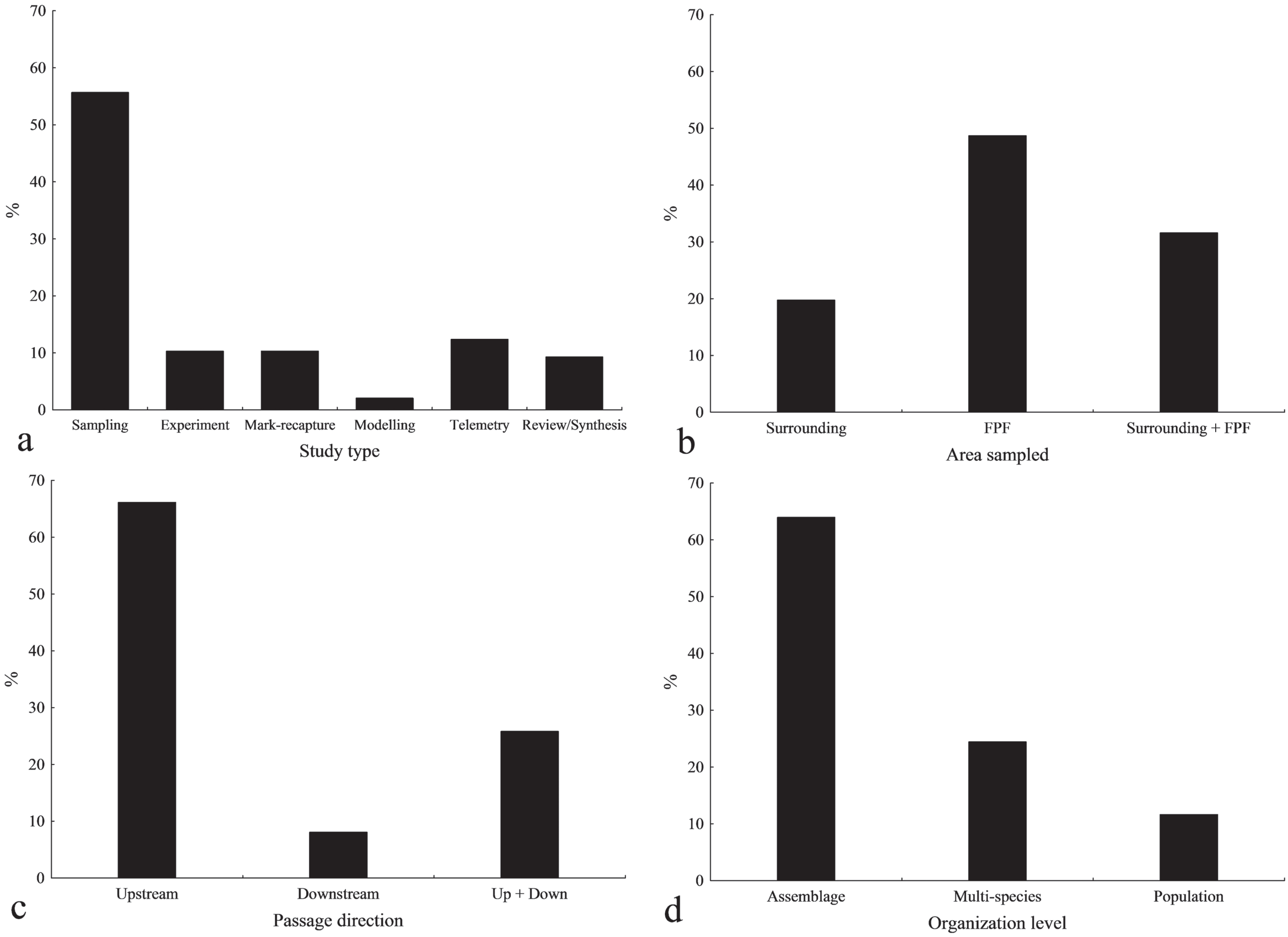

Fig. 6. Profile of studies that investigated fish passage facilities in South America. **a.** type of study; **b.** area sampled; **c.** passage direction; **d.** level of biotic organization.

Tab. 2. Migratory and non-migratory fish species retrieved from studies that investigated fish passage facilities and nearby sites. These species were recorded from population-level studies (see Fig. 6d). N = number of studies.

Species	N
Migratory	
Prochilodus lineatus	23
Pimelodus maculatus	13
Salminus brasiliensis	11
Megaleporinus elongatus	10
Piaractus mesopotamicus	9
Pseudoplatystoma corruscans	7
Megaleporinus obtusidens, *Pterodoras granulosus*	5
Megaleporinus reinhardti, *Salminus hilari*, *Prochilodus costatus*	4
Megaleporinus macrocephalus, *Pseudoplatystoma fasciatum*, *Rhinelepis aspera*, *Zungaro zungaro*	3
Hemisorubim platyrhynchos, *Leporinus* sp., *Rhaphiodon vulpinus*, *Zungaro jahu*, *Sorubim lima*	2
Pimelodus ornatus, *Pinirampus pirinampu*, *Pseudoplatystoma reticulatum*, *Brycon hilari*, *Salminus franciscanus*	1
Non-migratory	
Leporinus friderici	7
Hypostomus sp., *Schizodon borellii*, *Schizodon nasutus*	3
Astyanax sp., *Piabarchus stramineus*, *Leporinus octofasciatus*, *Metynnis maculatus*, *Myleus tiete*, *Oxydoras knerii*, *Pimelodus* sp., *Schizodon intermedius*	2
Pimelodus ornatus, *Ageneiosus brevifilis*, *Apareidon affinis*, *Astyanax* aff. *fasciatus*, *Astyanax altiparanae*, *Astyanax fasciatus*, *Auchenipterus nuchalis*, *Catathyridium jenynsii*, *Cichla kelberi*, *Cyphocharax santacatarinae*, *Geophagus brasiliensis*, *Hoplias malabaricus*, *Leporinus acutidens*, *Oligosarcus* aff. *jenynsii*, *Pimelodus absconditus*, *Pimelodus clarias*, *Iheringichthys labrosus*, *Pimelodus albicans*, *Rhamdia quelen*, *Rhinodoras dorbignyi*, *Schizodon knerii*, *Schizodon* sp., *Steindachnerina insculpta*	1

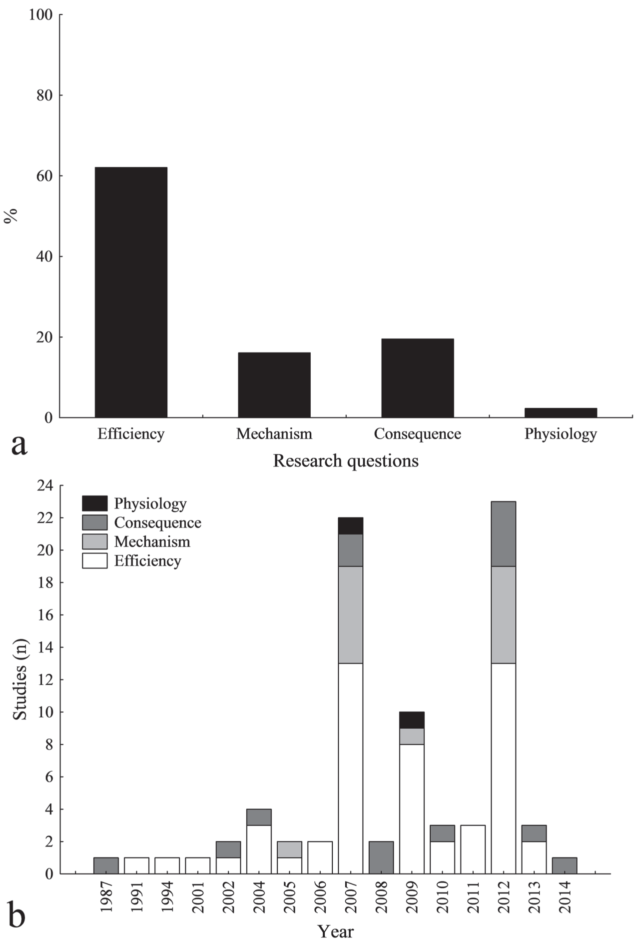

Fig. 7. Research questions addressed by studies, partitioned into categories *sensu* Roscoe, Hinch (2010). **a.** proportion of studies that addressed each research question; **b.** numeric distribution over the years.

few FPF (n = 25, mainly ladders) and biased towards specific topics. In particular, studies focused predominantly on the FPF themselves, addressing questions related to passage efficiency (*i.e.*, upstream passage) and rarely touching on conservation issues. This scenario indicates that the role of FPF in restoring river function and improving conservation remains poorly known, in accordance with claims from past investigations (*e.g.*, Agostinho *et al*., 2002, 2011; Pelicice, Agostinho, 2012; Pompeu *et al*., 2012). Such uncertainty may lead to inappropriate management decisions.

Studied facilities were distributed in different rivers of South America, but most are located in the Paraná River basin - where hundreds of dams regulate the flow of major river systems (Agostinho *et al*., 2016). Ladders were the most common fishways in our investigation, although other types have also been recorded. Historically, ladders were among the first facilities designed to assist salmonid migration (Katapodis, Williams, 2012). Due to their utility in particular hydraulic conditions (*e.g.*, high flow and discharge), manageable engineering aspects and lower costs, they gained popularity and became the main fishway technology in the world (Agostinho *et al*., 2007a). These aspects may explain why they are so popular in South America.

One important finding is that FPF were installed predominantly in specific spatial contexts, *i.e.*, major rivers and upper reaches of the basin. We also recorded FPF in small dams, but the majority is located in large dams. These patterns may be related to the common assumption that large dams cause stronger impacts, and that fish must reach headwaters to spawn. This is curious, however, because small dams also impede migratory movements (Cooney, Kwak, 2013), and dams currently regulate upper, middle and lower reaches of all river basins in the continent (Agostinho *et al*., 2016). More distressing is the fact that facilities are installed in contexts where connectivity to upstream and downstream reaches is severely limited. For example, all studied facilities have other dams located upstream or downstream, and many of these adjacent dams lacked FPF. These scenarios are in disagreement with the primary intention of fishways, *i.e.*, to restablish migratory routes along the river continuum to allow recruitment and natural population dynamics (Agostinho *et al*., 2007a; Pompeu *et al*., 2012). Therefore, considering that most FPF are located in upper reaches, and that many facilities are isolated, we conclude that systematic planning (basin-scale) has not guided the installation of FPF in South America. Indeed, other reasons have determined the installation of fishways, such as legal constraints, social demands or logistical/financial reasons (Agostinho *et al*., 2007a). This scenario may explain why some facilities lead fish to impoverished environments or may cause additional impacts (*e.g*., Pelicice, Agostinho, 2008; Pompeu *et al*., 2012). In principle, specific technical studies should determine the need for a FPF, based on previous assessments at the watershed scale (Agostinho *et al*., 2007a; Pompeu *et al*., 2012).

Most studies that evaluated FPF in South America were published in the last decade (2004-2014). A global-scale research survey also observed this trend (Roscoe, Hinch, 2010), indicating that fishway function has attracted attention only recently. High scientific publications in South America occurred in specific years. Most publications appeared during 2007 and 2012, when Neotropical Ichthyology published two special volumes dedicated to the subject (v. 5 and v. 10, both International Symposia on Fish Passages in South America). Therefore, future scientific production will probably depend on external motivation (*e.g*., International Conferences, financial incentives), especially if relevant data is held in grey literature (*e.g*., thesis, reports). It is important to emphasize that our study was extensive and probably gathered all relevant and accessible literature, but there might be valuable data in unpublished reports with restricted access. The publication of this literature must be encouraged, especially because we know little about its extent.

Research effort was unbalanced and concentrated on a limited group of facilities, located mainly in the Paraná and Tocantins river basins. Special attention has been devoted to the ladders at Lajeado, Peixe Angical, Igarapava and Porto-Primavera dams, the lift at Santa Clara dam, and the Canal da Piracema at Itaipu. This pattern is probably related to the focus of specific research groups and universities, which elected these fishways as study models. On the other hand, some FPF remain barely studied, such as those at Funil, Yacyreta and Canoas I and II. Other facilities are likely to exist that have not been studied; in fact, Pompeu, Martinez (2005) mentioned the existence of 50 ladders in South America. This information indicates that the number of studied facilities is low compared to the number installed. The fact that FPF are trivialized among managers (Agostinho *et al*., 2007a), which understand these facilities as efficient tools, must explain the paucity of investigations. Facilities are commonly installed without sound ecological information, and monitoring is absent or insufficient (Pompeu *et al*., 2012). Our literature survey, for example, found only post-installation studies, indicating that the decisions to build FPF are not typically based on *a priori* empirical assessments. In addition, the first evaluation of new FPF is usually delayed. The mean time elapsed between the beginning of the operation and evaluation was 3.3 years, but it reached decades in some cases. Older facilities tend to experience longer delays, probably because recent FPF are subjected to state laws, greater control by environmental agencies and social vigilance (Agostinho *et al*., 2007a). Delayed research prevents the assessment of management success, malfunctioning (*e.g*., selectivity, attraction; Agostinho *et al*., 2007a) and impacts (*e.g*., predation, ecological traps, source-sink, loss of genetic diversity; McLaughlin *et al*., 2012; Pelicice *et al*., 2015). In this context, fishways should be evaluated immediately after installation, older facilities should be regularly monitored, and results disseminated among researchers, managers and society.

Our investigation revealed that studies typically employ field sampling to evaluate passage efficiency focused on the fishway itself. This approach restricts understanding and leaves key questions unanswered, *e.g*., post-passage migration, spawning, recruitment, downstream passage and migration, and population persistence in the long-term (Agostinho *et al*., 2007b; Kraabol *et al*., 2009; Agostinho *et al*., 2011; Pompeu *et al*., 2012; Pelicice *et al*., 2015). For example, many species recorded inside the facility may not be able to complete passage, or may not reach critical habitats upstream. In this case, studies that use telemetry (*e.g*., Hahn *et al*., 2007), mark-recapture (*e.g*., Antonio *et al*., 2007) or evaluate the distribution of critical habitats (*e.g*., Pelicice, Agostinho, 2008) are essential to answer these questions.

One important aspect is the strong research bias toward upstream migration, which is probably inspired by the common assumption that safe upstream passage equals successful management (Agostinho *et al*., 2011; Pompeu *et al*., 2012). Migratory fishes in South America are potadromous, performing multiple upstream and downstream displacements throughout their life cycle (Carolsfeld *et al*., 2003; Godinho, Kynard, 2008). Lack of consideration for downstream movements and other post-passage issues, therefore, prevents inferences about management success. We cannot neglect the fact that all studies that investigated downstream passage found severe limitations, for both adult and young fish (Agostinho *et al*., 2007b; Lopes *et al*., 2007; Pelicice, Agostinho, 2008; Agostinho *et al*., 2011; Suzuki *et al*., 2011; Pelicice, Agostinho, 2012; Britto, Carvalho, 2013; Pelicice *et al*., 2015). For example, studies conducted at Lajeado and Peixe Angical fish ladders, Tocantins River, showed that downstream passage is negligible on a yearly basis. The average ascending:descending ratio was 1508:1 (Lajeado) and 644:1 (Peixe Angical), and many species performed only upward movements (Agostinho *et al*., 2011; Pelicice, Agostinho, 2012). As one-way passage can cause additional disturbance to fish populations (Pelicice, Agostinho, 2008; Britto, Carvalho, 2013; Pelicice *et al*., 2015), it is crucial that future evaluations include greater spatial scales and broader issues, beyond the FPF (Kraabol *et al*., 2009), and take population recruitment and persistence as the central management goal (Pompeu *et al*., 2012).

Regarding research questions (*sensu* Roscoe, Hinch, 2010), most studies addressed efficiency questions, *i.e*., issues related to fish passage, such as abundance and species composition within the fishway (*e.g*., Bowen *et al*., 2006; Makrakis *et al*., 2007a; Pompeu, Martinez, 2007), or the proportion of fish ascending and descending the facility (*e.g*., Agostinho *et al*., 2007d; Fernandez *et al*., 2007a; Makrakis *et al*., 2010). A smaller number addressed mechanism questions, which investigated how passage is affected by operation (*e.g*., Pompeu, Martinez, 2005), environmental variables (*e.g*., Fernandez *et al*., 2007b; Pereira-Assis *et al*., 2009a), and swimming ability (*e.g*., Santos *et al*., 2007; Assumpção *et al*., 2012; Santos *et al*., 2012). The fact that just a few papers addressed physiology and consequence questions is more troubling because these approaches provide essential information for management plans; efficiency and mechanism questions cannot, alone, determine management success and the impact of FPF on conservation. We emphasize that these research questions are complementary, so all must receive balanced attention. While some address small-scale and refined issues (*e.g*., passage efficiency, swimming ability), others address topics more related to management success (*e.g*., migration continuity and recruitment).

Studies that evaluated physiology and consequence questions investigated the effects of FPF on genetic diversity (*e.g*., Lopes *et al*., 2007; Ramos *et al*., 2012), predation pressure (*e.g*., Agostinho *et al*., 2012), and recruitment (*e.g*., Agostinho *et al*., 2004; Maia *et al.*, 2007; Pelicice, Agostinho, 2008; Suzuki *et al*., 2013; Pelicice *et al*., 2015). Some of these studies, however, were literature reviews, syntheses or were based on secondary data. Purely empirical investigations were rare and did not evaluate whether management enhanced recruitment. Different factors may explain why physiology and consequence questions have been neglected. For example, hydropower companies usually fund monitoring programs, and are motivated exclusively by legal requirements; consequently, assessments rely on easily measured variables, such as upstream passage. The lack of clear conservation goals also leads to superficial evaluations, where the number of ascending fish is used as proxy of management success. Another bias is the prevailing assumption that FPF are efficient when they allow upstream migration, which puts heavy weight on upstream passage. In this case, the concept of successful passage must be replaced by the concept of successful management, where population persistence becomes the central goal (Pompeu *et al*., 2012). Another problem is that research is discontinuous and not systematized. Many FPF were studied just once, and long-term data are unavailable; research is commonly based on simple metrics (*e.g*., fish abundance and composition within the fishway), since studies on recruitment are expensive and more complex, involving different variables and wide spatial-temporal scales. In addition, each study investigated a single FPF (with few exceptions), providing little insight for basin-scale management.

Given the growing demand for electricity in South America, rivers have been progressively targeted for hydropower development (Agostinho *et al*., 2016; Less *et al*., 2016; Winemiller *et al*., 2016). Fluvial ecosystems are increasingly vulnerable to river regulation and impoundments, and FPF will continue to be installed with the intent of mitigating impacts. However, controversies and skepticism about their conservation role is growing (*e.g*., Agostinho *et al*., 2002, 2007a; Oldani *et al*., 2007; McLaughlin *et al*., 2012; Pompeu *et al*., 2012; Pelicice *et al*., 2015; Kemp, 2016), and the present study revealed that we have limited understanding about the functioning, management success and conservation value of fishways in South America. We hope that our study will guide future research to take place in a broader context, considering issues that range from fish passage efficiency to recruitment and population persistence. This information will allow better decisions concerning the installation of new facilities, and will clarify whether FPF can play a positive role in the conservation of Neotropical fish diversity.

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