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The decline of fisheries on the Madeira River, Brazil: The high cost of the hydroelectric dams in the Amazon Basin

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Abstract

Despite being considered beneficial by providing a clean and renewable source of energy, the construction of hydroelectric dams has extremely negative implications for Amazonian fisheries. This study investigated the impacts of the Santo Antônio and Jirau hydroelectric dams on the fishery stocks of the Madeira River. This investigation was based on fish catch data from the Z-31 fishing colony, located in the municipality of Humaitá, in Amazonas State, Northern Brazil. Data were collected daily and provided information on the date of return from each trip, the fish species targeted, and the total catch (kg) between January 2002 and September 2017. The results indicated reductions of 39% in the mean annual catch and 34% in the mean monthly catches. These results highlight the high price paid by local fish communities for the development of hydroelectric power in the Amazon basin.

KEYWORDS
biodiversity, environmental impact, fish fauna, fishing colony, fluviometry, impoundments

1 | INTRODUCTION

The Madeira River basin is one of the most important ecosystems for Amazonian fisheries (Doria, Ruffino, Hijazi & Cruz, 2012; Goulding, 1979). The high productivity of the Amazon basin generally is related not only to it being the world's largest hydrographic basin but also the highly dynamic relationship between the terrestrial environment and the aquatic ecosystem, which is a characteristic of fluvial ecosystems located in tropical and equatorial regions (Junk, 2001). In this region, fishing patterns and the quantity and quality of the fish caught are determined primarily by the hydrological cycle, which regulates the formation of shoals and the timing of their migrations (Batista & Petrere, 2003; Junk, Bayley & Sparks, 1989).

The equilibrium between terrestrial and aquatic environments in the Amazon basin is threatened by the construction of hydroelectric dams. The hydroelectric potential of the region's rivers has led to major advance in this sector (Soito & Freitas, 2011), and 100 dams are already in operation within the whole Amazon region, while another 137 are planned or under construction in the countries that make up this region (Lees, Peres, Fearnside, Schneider & Zuanon, 2016; Tundisi, Goldemberg, Matsumura-Tundisi & Saraiva, 2014). Plans for the Brazilian energy sector include the expansion of the hydroelectric potential by 6.8 GW, with 16 new dams, by 2026, with 57% of this potential being provided by dams located in the Amazon basin (MME/EPE, 2017).

Despite being considered beneficial, by providing a clean and renewable source of energy, hydroelectric dams provoke major impacts on the hydrological cycle (Timpe & Kaplan, 2017), causing longitudinal disturbances throughout the course of the river, as predicted by the Ward and Stanford (1995) serial discontinuity concept.

One of the most obvious effects of river damming on the hydrological cycle is the modification of the patterns of river discharge and fluviometry (Junk & Mello, 1990; Winemiller et al., 2016). These impacts may reduce the deposition of nutrients on the floodplain and in marginal lakes (Zahar, Ghorbel & Albergel, 2008) and change the morphological configuration of the river channel, such as the number and intensity of the erosional processes affecting the margins, and the physical–chemical characteristics of the water (Lobato et al., 2015).

The construction and subsequent operation of hydroelectric dams provoke major environmental impacts (e.g., loss of habitats and hydrological shifts), which have highly negative implications for the fundamental ecological processes that maintain the biological diversity of the system and sustain local fish stocks (Agostinho, Pelicice & Gomes, 2008; Bunn & Arthington, 2002; Pelicice et al., 2017). These environmental changes may interrupt fish migration routes, modifying the abundance, composition and trophic configuration of their communities, including an increase in the abundance of some species; whereas the populations of other species may be greatly reduced or even become extinct (Agostinho, Miranda, Bini, Gomes & Thomaz, 1999).

The change from a lotic to a lentic environment also favours the invasion of non-native species, creating a high risk of regional colonization (Assis, Dias-Filho, Magalhães & Brito, 2017). This type of impact is not yet common in Amazon ecosystems. According to Leprieur, Beauchard, Blanchet, Oberdorff and Brosse (2008), hydrological alterations and biological invasions are considered the two largest threats to aquatic native biota.

The Madeira River in northern Brazil is among the ecosystems that have suffered from the construction of hydroelectric dams. The Santo Antônio and Jirau dams were inaugurated on the middle Madeira River in 2012. While these dams were planned to guarantee the energy security of Brazil, their impacts on the local ecosystem and fisheries are still poorly understood, considering that most of the commercial fish species found on the Madeira River are migratory (Barthem et al., 2017). This is a major issue, given that these fish are migratory (e.g., *Mylossoma* spp., *Prochilodus nigricans* Spix and Agassiz, *Semaprochilodus* spp.) and large-bodied catfish (*Brachyplatystoma* spp. and *Pseudoplatystoma* spp.) that undertake long-distance longitudinal migrations, and are among the most threatened by dam construction (Fearnside, 2014). Stocks of most of the species of commercial interest may suffer major fluctuations due to the presence of physical barriers to their migration and the changes in the hydrological regime of the Madeira River.

Given the importance of fisheries in the Amazon region, the impacts of hydroelectric dams on fish stocks may have socio-cultural and economic implications for local communities. Fishing was practiced in the Amazon well before European colonisation, and fish is an essential component of the diet of its riverside and indigenous peoples (Furtado, 2006). In the present day, fish continues to be an essential resource for human communities throughout the region where it is a principal source of both animal protein and income (Cerdeira, Ruffino & Isaac, 1997).

Major development projects will inevitably have some impact on any ecosystem. However, the proliferation of hydroelectric dams in the Amazon region and the acceleration in the construction of these plants, as is the case with Belo Monte Hydroelectric Complex on the Xingu River (Fitzgerald et al., 2018), indicates that their impacts on local fisheries may not only be underestimated, but may exceed the resilience of local ecosystems. In this context, this study investigated the influence of the hydroelectric complex implemented recently on the Madeira River on the local fisheries, using the database available from fisheries located downstream from the dams. This study tested the hypothesis that the instability of the flood pulse caused by the construction of the dams has caused a significant reduction in the fish stocks of the Madeira basin.

2 | METHODS

2.1 | Study area

This study was based on the database of fishery catches landed in the municipality of Humaitá, in the south of the Brazilian state of Amazonas, 675 km south of the state capital, Manaus. The municipality of Humaitá has an area of approximately 34,430 km^2, and around 52,000 inhabitants (IBGE, 2017).

The Madeira River is part of the Amazon basin and is the principal tributary of the right margin of the Amazon. The headwaters of the Madeira are located in the Bolivian Andes, and the river is formed by the confluence of the Beni and Mamoré rivers (Goulding, Barthem & Ferreira, 2003). The Madeira has a total length of 3,240 km, of which 1,425 km are within Brazil, where this river traverses the states of Rondônia and then Amazonas before discharging into the Amazon River near the town of Itacoatiara, metropolitan region of Manaus (Costa, 1998). The mean discharge of this river is 31,200 m^3/s (Guyot, 1993). According to the Köppen classification system, local weather belongs to group A (rainy tropical) and type Am (monsoon rains), with a short dry period, and annual precipitation ranging from 2,250 to 2,750 mm. The mean annual temperature ranges from 24 to 26°C.

The Santo Antônio hydroelectric dam (08°48′ S, 63°56′ W) is 7 km upstream from Porto Velho, capital of the Brazilian state of Rondônia, and 175 km from the municipality of Humaitá, in the state of Amazonas (Figure 1). The construction of this dam began in September 2008, and the reservoir began to fill in early 2011, when the first of the sluice gates was closed. The first turbines began to operate on 30 March 2012, and in November 2016 the power plant was completed with 50 turbines installed with a total production capacity of 3,568 MW. The Jirau hydroelectric dam (09°15′ S, 64°38′ W) is 100 km upstream from Porto Velho and 263 km from Humaitá (Figure 1). In October 2012, the river was dammed to fill the Jirau reservoir. The first turbine began to operate in September 2013, and the power station was completed in December 2016 with 50 turbines and a capacity of 3,750 MW.

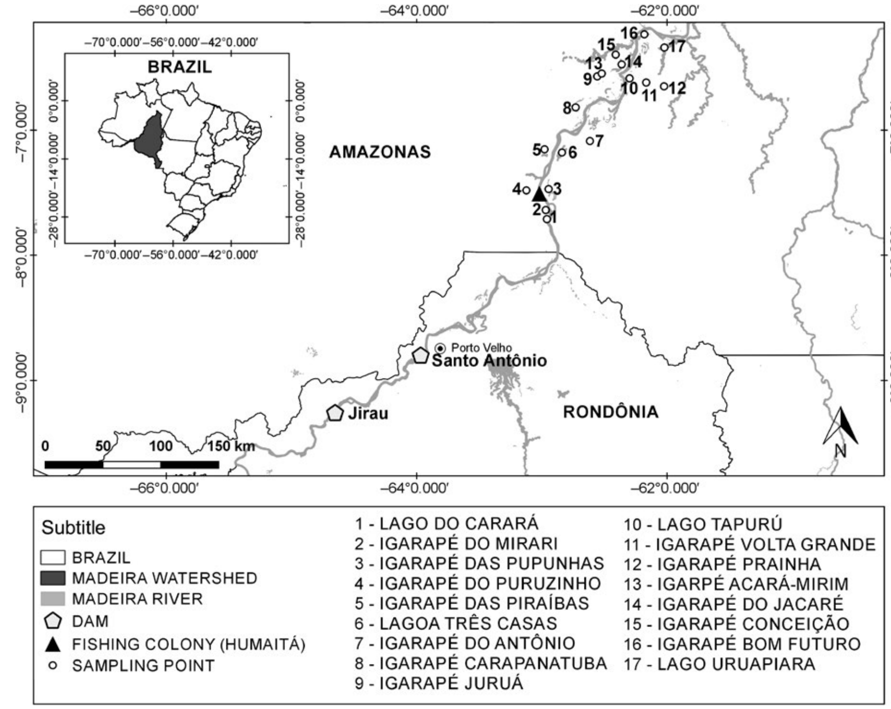

FIGURE 1 Fishing ground of the Z-31 (Dr. Renato Pereira Gonçalves) fishing colony based on the municipality of Humaitá, Amazonas state, Brazil, and the location of the Santo Antônio and Jirau dams on the Madeira River in Rondônia State

2.2 | Sample collection

The influence of the Santo Antônio and Jirau dams on local fishery catches was evaluated through analysis of the productivity database of the "Dr. Renato Pereira Gonçalves" (Z-31) fishing colony, covering the period between January 2002 and September 2017. The catches landed by this colony are taken from 17 fishing grounds located downstream from the dams (Figure 1). A total of 1,655 fishers are registered as members of the Z-31 fishing colony.

Catch data were recorded daily at the colony and include the fishing ground (point), the date of the beginning and the end of each fishing trip, type of fish caught and total catch (kg). All commercial catches obtained in the region are landed at the colony's floating pier for the collection of the catch data. River-level data were obtained from the Humaitá station of the hydrological information system with the Agência Nacional de Águas (www.hidroweb.ana. gov.br).

2.3 | Data analyses

In 2013, the floating pier of the fisher colony was removed from the Madeira River to make way for the construction of flood prevention works by the Humaitá town council. This led to the suspension of data collection between January and October 2013, so the data from 2013 were excluded from the analyses. The data on the catches of the tambaqui, *Colossoma macropomum* (Cuvier), were also excluded from the analyses because many of the specimens landed were raised in fish farms and were thus isolated from the direct effects of the impact of damming of the Madeira.

For the analysis of the impacts of the dams on the fishery catches, the data were divided into "Before" (prior to damming) and "After" (post-damming) samples. As the sluices gates of the Santo Antônio dam were closed completely in July 2011, the data for the period between January 2002 and July 2011 were allocated to the "Before" sample, whereas those from August 2011 to September 2017 were allocated to the "After" sample. The sluice gates of the Jirau dam were shut off completely in October 2012.

The trends in the fishery catches over time were evaluated through a descriptive analysis of the catch history. Mann–Kendall test for the detection of monotonic trends was also applied to determine the trends in fishery production during the "Before" and "After" samples.

Analysis of variance (ANOVA) was used to verify the significance of the variation in fishery catches among the different phases of the hydrological cycle, and between periods (Before and After). Due to temporal dependence of the data, ANOVA was performed with the standardized errors of a model that included the temporal dependence of the data. A serial autocorrelation test was performed with the standardised errors and was not significant.

Impacts of fluviometric changes on fisheries were evaluated through a descriptive analysis of the catch history. Thereafter, a linear regression analysis was run to verify the extent to which the changes in the fluviometry (level) of the Madeira River after damming influenced fishery production. The regression was based on the variation between the periods (before and after) in the mean fishery harvest with the mean variation in fluviometry (river level). The mean monthly variation in fluviometry was calculated based on: $\Delta\overline{FI}_i = \overline{FI}_{Ai} - \overline{FI}_{Bi}$ (I), where $\Delta\overline{FI}_i$ is the mean variation in fluviometry between periods (before and after) in each month *i* (from January to December), $\overline{FI}_{Ai}$ = mean fluviometry after damming of the river in each month *i*, and $\overline{FI}_{Bi}$ = mean fluviometry before damming in each month *i*. The $\Delta\overline{FI}_i$ values were grouped in five, 100-cm classes: −100–0, 0–100, 100–200, 200–300 and 300–400.

TABLE 1 Fish landings at Humaita, Amazonas state from 2002-2017

Year	Total annual catch (kg)	Minimum monthly catch (kg)	Maximum monthly catch (kg)	Mean monthly catch	±Standard deviation (kg)
2002	294,355	8,851	61,239[a]	24,530	14,962
2003	299,300	10,728	44,163	24,942	8,880
2004	247,664	15,679	26,347	20,639	3,411
2005	248,065	14,733	29,802	20,672	4,594
2006	350,269[a]	11,382	56,321[a]	29,189[a]	13,973
2007	314,895	10,635	34,735	26,241	7,625
2008	247,119	11,123	28,214	20,593	6,028
2009	162,353	6,452	25,487	13,529	5,276
2010	238,995	5,910	39,744	19,916	12,084
2011	407,554[a]	12,261	52,274[a]	33,963[a]	14,115
2012	243,165	6,346	36,139	20,264	9,684
2014	158,560	2,174[b]	29,094	13,213	9,388
2015	94,514[b]	1,607[b]	16,625	7,876[b]	4,594
2016	156,379	8,112	19,560	13,032	3,353
2017	101,054[b]	7,424	15,588	11,228[b]	2,230
Total	3,564,241	[c]	[c]	[c]	[c]

[a]"Peaks" in fishery production. [b]Lowest fishery productivity. [c]The total for these variables (min, max, mean, and *SD*) would not clearly express the results for these columns.

Mean variation in fishery production was calculated using: $\Delta\overline{P}_i = \overline{P}_{Ai} - \overline{P}_{Bi}$ (II), where $\Delta\overline{P}_i$ = mean variation in fishery production between periods (before and after) in each month *i*, $\overline{P}_{Ai}$ = mean fishery production after the damming of the river in each month *i*, and $\overline{P}_{Bi}$ = mean fishery production before damming in each month *i*. The result of mean variation in fishery production was regressed on the classes recorded for mean variation in fluviometry. All statistical analyses were run using the software R 2.14.1 (R Core Team 2011) (Sokal & Rohlf, 1995).

3 | RESULTS

3.1 | Analysis of fisheries

During the study period as a whole (January 2002 to September 2017), the total fishery catch was 3,564,241 kg, with an annual mean of 237,616 kg (Table 1). The most productive years were 2011, the year of damming, and 2006 during the Before period. The least productive years were recorded after damming in 2015 and 2017 (Table 1).

The highest monthly fishery production was recorded in July 2002, and the lowest in March 2015 (Figure 2; Table 1). In addition to 2002, peaks in the monthly catches were recorded in April 2006 prior to damming and April 2011 during the damming period (Figure 2, Table 1). No monthly peaks were recorded after damming. The second lowest monthly catch was recorded in December 2014.

Mean monthly fishery productivity before damming was 22,876 kg, while after damming it declined to 15,056 kg (Figure 2), a decline of 34% in the mean monthly production of fish. Considering only years with a full set of monthly records, the mean annual fishery production was 267,001 kg prior to damming (2002–2010) (Table 1) and 163,155 kg for the period after damming (2012–2016). This represents a 39% decline in the annual fishery production, based on the catches landed in the municipality of Humaitá.

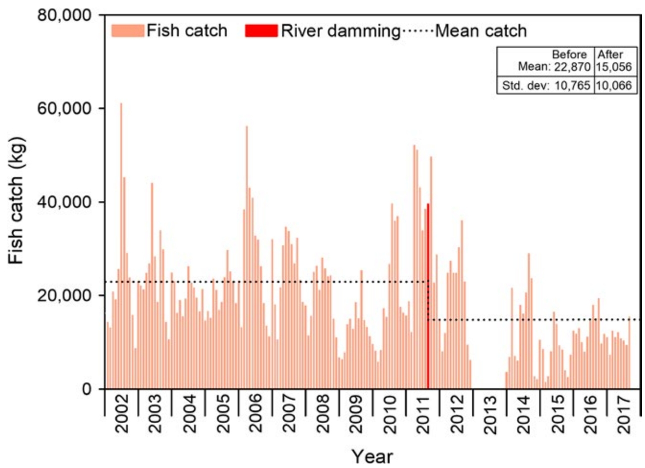

FIGURE 2 Fishery production (kg) landed in the municipality of the municipality of Humaitá, Amazonas state, Brazil, between January 2002 and September 2017. The vertical red line represents the initial damming of the Madeira River (July 2011). Note that the data from 2013 were not included here

Mann–Kendall test did not reveal any significant tendency for any increase or decline in fishery production (Figure 3) prior to

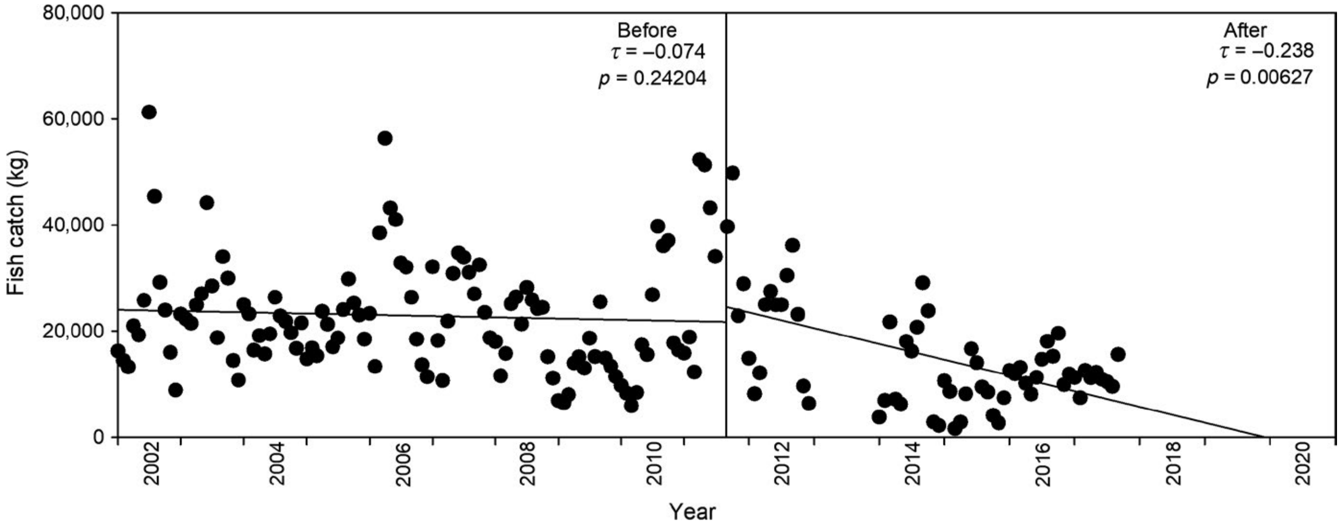

FIGURE 3 Monthly fish catch at Humaitam Amazona state before (2002-2011) and after (2011-2017) of the Medeira River. Tau (use symbol) is Kendall rank correlation

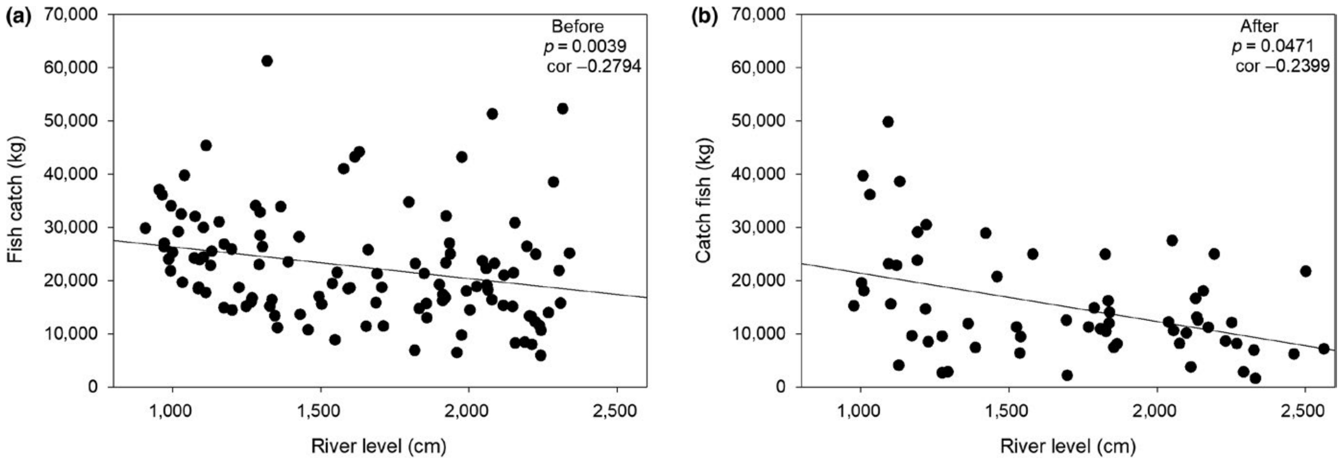

FIGURE 4 Linear regression of the fishery production landed in the municipality of Humaitá, Amazonas state (Brazil) on the level of the Madeira River before (a) and after (b) damming the Madeira River

damming of the river. After damming, however, a significant tendency for declining production was recorded (Figure 3).

3.2 | Influence of the hydrological cycle on fisheries

A significant difference in the mean fishery production among the different phases of the flood pulse was found both before (Figure 4a) and after (Figure 4b) damming of the river (ANOVA: $F = 4.925$, $N = 171$, $df = 3$, $p < 0.001$). A negative (Pearson) correlation was found between fishery production and the river level; that is, fishery productivity tended to be higher when the river was at its lowest levels (Figure 4).

3.3 | Impacts of fluviometric changes on fisheries

Considerable differences were observed in the fluviometric cycle of the Madeira River following damming (Figure 5a) when at least 1 month in a given year exceeded the maximum level recorded historically (prior to damming) for that month. River levels also varied more among years, and there was less homogeneity in the fluviometric patterns following damming of the Madeira River (Figure 5a).

Comparison with the historical means indicated a pronounced increase in the mean variation of river levels between March and October following damming (Figure 5b, Table 2), and greater discrepancies were recorded between May and August during the ebb period when the river level falls after the annual peak. This indicates that after damming the river level remained higher during the ebb period but reached a lower level by November and December (Figure 5b, Table 2). This indicates that the beginning of the flood period was characterised by lower river levels after damming of the Madeira, although the variation levelled off in January and February as the river flooded.

The greatest variation in river levels was observed in July with a mean value of 1,328 cm being recorded before damming and 1,661 cm afterwards (Figure 5b, Table 2). The smallest difference was recorded in January with a mean of 1,881 cm before damming and 1,884 cm afterwards (Figure 5b, Table 2).

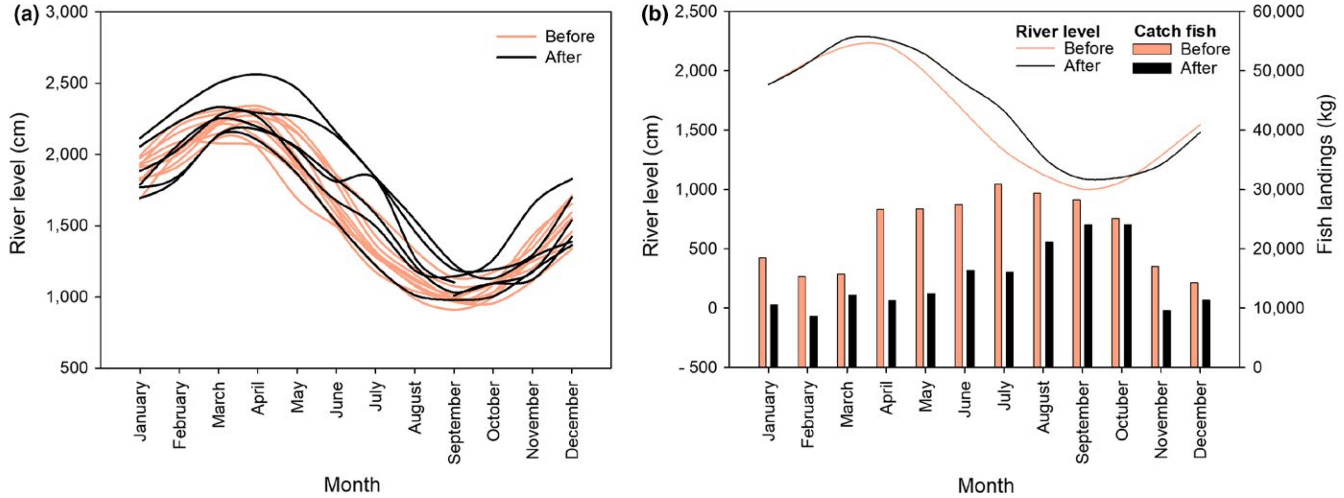

FIGURE 5 Mean monthly river level of the Madeira River (a) and fishery landings at Humaita, Amazonas state before (2002-2011) and after (2014-2017) closing dams on the Madeira River (b)

A reduction in mean catches in all months was found following damming of the Madeira River (Figure 5b, Table 2). The decline in catches was most pronounced between April and July (ebb period), which coincides with the period most affected by the increase in the mean fluviometry of the Madeira River when the variation exceeded 300 cm (Figure 5b, Table 2). Catches were least affected in October, December and March when the variation in the river level did not exceed 100 cm (Table 2). Fishery production declined most in April with a reduction of 15,414 kg (a decrease of 57.8%) and least in October with a reduction of only 1,055 kg (4.2%).

The highest mean fishery production was recorded in July and August (ebb period) prior to damming of the river (Figure 5b, Table 2). Following damming, mean production was highest in September and October in the dry season; December was the least productive month in the period prior to damming, although February was the least productive month following damming (Figure 5b, Table 2).

Linear regression was used to compare mean variation in river levels ($\Delta\overline{FI}_i$) with that in fishery production ($\Delta\overline{P}_i$) between the before and after damming periods (Table 3). A negative trend was found; that is, the greatest losses in production were recorded in the classes that had the greatest increase in river levels following damming of the Madeira River (Figure 6). According to the regression, for each 100 cm increase in the mean variation of the level of the river after damming, there was a decrease in the catch of approximately 2.864 kg of fish, a reduction of 12.5% for each increase in class (Figure 6).

The 300–400 class had the greatest effect on the catches (Figure 6, Table 3). By contrast, the reduction in the mean river level (−100–0 class) had the least effect on fishery production. Considering the overall loss in fishery production (48,896 kg) recorded (Table 3), 30% was concentrated in the 300–400 class, and only 12% in the −100–0 class. The regression indicated that, independently of any variation in the level of the river, damming alone was responsible for a reduction of 2,305 kg (10.1%) in the mean fishery production (Figure 6).

4 | DISCUSSION

4.1 | Declining fisheries

Following damming of the Madeira River, mean monthly catches landed at Humaitá decreased 34%, and mean annual fishery production declined 39%. The regression analysis revealed a tendency for decreasing fishery production following damming. A similar decline in fishery production has been recorded in other aquatic ecosystems of the Amazon region impacted by hydroelectric dams. Following the construction of Tucuruí dam on the Tocantins River, Brazil, for example, Santana, Bentesm, Homma, Oliveira and Oliveira (2014) found that the contribution of the downstream fisheries to the total local production decreased from 44% to 25%. Forty years after damming of the Tocantins River, the situation remains unfavourable, and the downstream fisheries are unable to satisfy the demand for fish of the resident population. Hallwass, Lopes, Juras and Silvano (2013) also reported a decrease in fish abundance and a possible local extinction of a commercial fish species (*Semaprochilodus bram*) after the Tocantins River dam.

Besides the Amazon region, the impacts of hydroelectric dams on the fish fauna and the decline of important commercial species have also been found in other aquatic ecosystems around the world (e.g., Agostinho et al., 2008; Assis et al., 2017; Dugan et al., 2010; Neraas & Spruell, 2001; Stone, 2016; Zhong & Power, 1996). For instance, a study of the effects of the Tallowa dam on the Shoalhaven River (south-east Australia) found a reduction in the abundance of four species of migratory fish and possibly the extinction of another ten species (Gehrke, Gillgian & Barwick, 2002). Other relevant studies using modelling of future scenarios verified that the construction of a hydroelectric dam in the Mekong River could lead to a fish production

TABLE 2 Monthly river levels and fishery production landed in Humaitá, Amazonas (Brazil), before (January 2002–July 2011) and after (August 2011–September 2017) damming of the Madeira River, with the variation between the periods (Before and After)

			January	February	March	April	May	June	July	August	September	October	November	December
River level (cm)	Before	Min	1,686	1,921	2,077	2,045	169	1,494	1,174	987	908	955	1,112	1,335
		Max	1,991	2,237	2,309	2,339	2,195	1,858	1,599	1,328	1,132	1,173	143	1,711
		Total	18,813	20,714	22,067	22,152	19,844	16,522	13,281	10,116	9,028	9,575	11,551	13,911
		Mean	1,881	2,071	2,207	2,215	1,984	1,652	1,328	1,124	1,003	1,064	1,283	1,546
		Standard deviation	92	103	73	108	159	137	118	93	66	66	97	140
	After	Min	1,694	1,838	2,134	2,099	1,865	1,526	1,219	1,011	977	1,003	1,121	1,363
		Max	2,114	2,327	2,502	2,563	2,462	2,156	184	154	1,228	1,191	1,294	1,697
		Total	9,421	10,326	11,358	1,132	10,686	9,446	8,303	7,639	6,538	551	6,043	7,406
		Mean	1,884	2,065	2,272	2,264	2,137	1,889	1,661	1,273	109	1,102	1,209	1,481
		±Standard deviation	188	219	153	181	231	261	270	199	103	68	73	138
		Variation in the mean	3	−6	65	49	153	237	333	149	87	38	−75	−64
Fish catch (kg)	Before	Min	6,866	6,452	591	8,408	15,116	12,992	18,631	1,517	21,794	14,896	13,369	8,851
		Max	32,102	2,321	38,489	56,321	51,289	44,163	61,239	45,352	36,064	37,042	23,482	21,518
		Total	184,958	153,299	157,420	266,665	267,362	275,141	309,187	254,752	253,852	2,261	153,473	128,582
		Mean	18,496	1,533	15,742	26,667	26,736	27,514	30,919	28,306	28,206	25,122	17,053	14,287
		Standard deviation	7,538	5,582	9,139	15,481	12,116	12,152	11,985	9,755	4,588	7,074	3,778	4,507
	After	Min	3,753	6,903	1,607	2,812	6,197	10,907	10,425	9,434	8,488	4,076	2,654	2,174
		Max	14,844	11,954	21,713	24,974	27,488	24,929	24,958	38,596	39,664	49,781	22,846	28,894
		Total	52,963	43,073	61,075	56,261	62,144	81,742	80,276	126,808	144,211	120,33	47,846	56,721
		Mean	10,593	8,615	12,215	11,252	12,429	16,348	16,055	21,135	24,035	24,066	9,569	11,344
		Standard deviation	4,154	198	7,135	8,331	8,697	5,748	5,409	11,602	12,703	16,448	8,209	10,402
		Variation in the mean	−7,903	−6,715	−3,527	−15,414	−14,307	−11,166	−14,864	−7,171	−4,171	−1,055	−7,483	−2,942

TABLE 3 Results of equations I ($\Delta\overline{FI}_i = \overline{FI}_{Ai} - \overline{FI}_{Bi}$) and II ($\Delta\overline{P}_i = \overline{P}_{Ai} - \overline{P}_{Bi}$)

Class of mean variation in river level (cm)	Mean fishery production (kg)		Variation mean do catch fishery (kg)	
($\Delta\overline{FI}_i = \overline{FI}_{Ai} - \overline{FI}_{Bi}$)	Before ($\overline{P}_{Bi}$)	After ($\overline{P}_{Ai}$)	$\Delta\overline{P}_i$	Overall loss (%)
−100–0	15.556	9.843	−5.714	−12
0–100	22.846	16.432	−6.414	−13
100–200	27.521	16.782	−10.739	−22
200–300	27.514	16.348	−11.166	−23
300–400	30.919	16.055	−14.864	−30
Total	124.357	75.460	−48.896	−100

loss up to 4%, which is equivalent to an annual decrease of approximately 25,300 t (Ziv, Baran, Nam, Rodríguez-Iturbe & Levin, 2012).

The construction of hydroelectric dams in Amazonian ecosystems represents a major risk for the local fish fauna, especially considering that fishery productivity in this region reflects the enormous diversity of fish species found in the Amazon basin. Approximately 920 fish species are estimated to occur in the Madeira River basin, around a third of all the known fish diversity of the Amazon region (Ohara et al., 2013), which is the highest of any hydrographic basin anywhere in the world (Queiroz et al., 2013).

The decline in catches recorded in the present study may have a negative direct impact on the economy of the local fishing communities. In the Amazon region, fisheries play an important role in the creation of jobs and the generation of income, as well as supplying both national and foreign markets (Almeida, Lorenzen & McGrath, 2004). Tundisi et al. (2014) estimated that the fishery production of the Amazon region contributes US$200 million/year to the region's economy and supports a workforce of 200,000 commercial fishers. Assuming a mean price of US$3.30 per kg for the principal fish species (e.g., *C. macropomum*, *Cichla ocellaris*, *P. nigricans*) exploited by commercial fisheries in the Amazon region (Lima, Almeida, Teixeira & Melo, 2016), the decline in the fishery production in the municipality of Humaitá would represent a mean loss of approximately US$342,000 of income per year. In this case, the construction of the Santo Antônio and Jirau dams has already cost the fishers of the Humaitá colony more than one and one half million dollars in lost revenue. These values would be even higher if the impacts on the secondary economic sectors related to the fisheries are considered, such as ice factories and suppliers of fishing equipment (i.e., gill nets), boats, outboard engines, outboard oil/fuel and provisions.

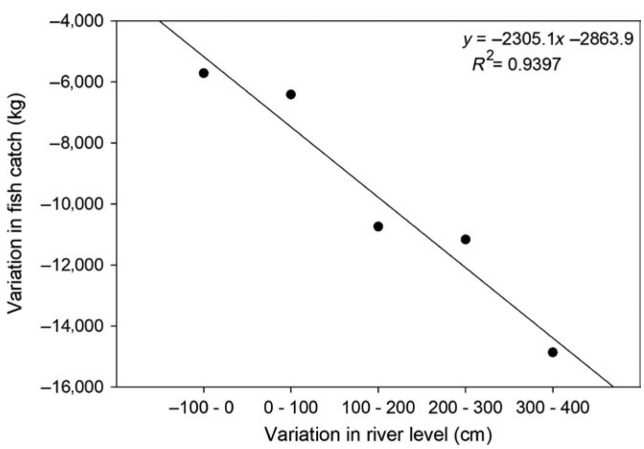

FIGURE 6 Linear regression of the mean variation in the river level on the difference mean fishery production before and after damming

In addition to the impacts on the economic sector, the decline in fishery resources on the Madeira River may also affect the subsistence of local families. In the Amazon region, the *per capita* consumption of fish is among the highest in the world, with an estimated mean consumption of 369 g per person per day or 135 kg/year (Cerdeira et al., 1997). On the Brazilian sector of the Madeira River alone, six major fishing colonies at Guajará-Mirim, Porto Velho, Humaitá, Manicoré, Borba and Nova Olinda do Norte are likely to have their consumption of fish affected (Boschio, 1992; Cardoso & Freitas, 2007; Doria et al., 2012; Santos, 1987). In other words, the 39% reduction in the annual supply of fish on the Madeira River observed in the present study will not only affect the production of the region's commercial fisheries but will also alter the diet of the local human populations that depend on fish for their animal protein needs.

The social impacts brought by hydroelectric development lead to a reflection about the future of fishers who lose their livelihoods based on fishing. The lack of income sources and food insecurity may result in marginalisation (Kirchherr & Charles, 2016), and it could aggravate social conflicts in the Amazon region. According to the World Dams Commission (WCD, 2000), the probability of successful adaptation by fishing communities in the face of dam-affected ecosystem degradation is low. This scenario may increase illegal practices as an easier way of obtaining income, such as drug trafficking, illegal hunting, illegal logging and biopiracy. Bui and Schreinemachers (2011) found that after the construction of the Son la hydroelectric dam in north-eastern Vietnam, the resettled fishermen had to complement their family income by collecting forest products, increasing pressure on forest resources.

It is also important to highlight other impacts that may be generated by declining fisheries in ecosystem services that are rarely taken into account, such as cultural and recreational services, disease control (e.g., schistosomiasis and malaria) and transport of nutrients, carbon and minerals (Holmlund & Hammer, 1999). Another worrying issue is the reduction of populations of frugivorous species (e.g., *Brycon* spp., *C. macropomum*, *Piaractus brachypomus*, *Triportheus* spp.), which have an important ecological function in seed dispersal (Costa-Pereira & Galetti, 2015). The tambaqui (*C. macropomum)*, for example, disperses the seeds of at least 76 plant species (Correa, Costa-Pereira, Fleming, Goulding & Anderson, 2015) and can disperse them kilometres away from their place of origin (Anderson et al., 2018). According to Valiente-Banuet et al. (2015), the disruption of seed dispersal mutualisms directly affects plant reproductive success and threatens biodiversity of the forests.

Hydroelectric dams are a relatively recent feature on the Madeira River, and the long-term effects of these dams must be analysed systematically. However, considering the importance of fisheries in the Amazon region, many authors have warned of the potential impacts of dams on the local fish fauna (e.g., Anderson et al., 2018; Cella-Ribeiro et al., 2015; Duponchelle et al., 2016). One of the main problems discussed by the authors is related to blockage of fish migration. According to Anderson et al. (2018), newly built dams on the Madeira River can modify the habitat for these species and create insurmountable barriers to their movement along the river corridors. They further stated that these impacts will be worsened by future climate change. Fearnside (2014) reported that 1 year after the construction of the Santo Antônio dam, most migratory catfish (e.g., *Brachyplatystoma* spp.) were no longer seen passing through the dam's fish ladders. The reduced volume of water in the ladder is apparently insufficient to attract the fish towards its entrance, and these fish instinctively follow the river's principal current. These reported facts are worrisome because blocking migratory routes can affect the reproductive biology and life cycles of migratory fish species (Agostinho, Gomes, Veríssimo & Okada, 2004; Winemiller et al., 2016) and thereby compromise the fish stock viability in the region.

This evidence indicates that the reduction in fish stocks at Humaitá may be, at least partly, related to blocking of migratory routes on the Madeira River. According to the linear regression, independently of any variation in the level of the river, damming alone was responsible for a reduction of approximately 10% in the mean fishery production. Although there are other dam impacts that may be related to the decline of the fishing (disregarding the hydrological changes). It is likely to affirm that part of the fall is exclusively related to the migratory routes blocking. This conclusion is reinforced by the majority of commercial fish species of the Madeira River being long-distance longitudinal migrators, such as some characiformes (e.g., *Brycon* spp., *Prochilodus* spp. *and Semaprochilodus* spp.) (Araujo-Lima & Ruffino, 2003) and siluriforms (e.g., *B. rousseauxii*, *B. platynemum*, *B. juruense and B. vaillantii*) (Barthem et al., 2017). If Santo Antônio and Jirau dams are reducing migration rates on the Madeira River, as suggested by Fearnside (2014), the populations of important species for commercial fishery production may be declining, which would account for the observed reduction in fishery landings at the Humaitá fishing colony.

Given the ample area of dispersal of the commercial fish species found on the Madeira River, blocking the migration routes by the dams may also have impacts on the fisheries in other parts of the Amazon basin. Fearnside (2014) pointed out that the newly constructed dams may reduce the fishery stocks not only in Brazil, but also in Bolivia and Peru. The spawning grounds of the goliath catfishes (*Brachyplatystoma* spp.), for example, lie upstream from the Santo Antônio and Jirau dams, whereas they complete their life cycle downstream, undergoing migrations of up to 3,000 km (Barthem et al., 2017). Given the importance of these catfish as a fishery resource throughout the Amazon basin, any reduction in their populations will cause social and ecological impacts far beyond the limits of the Madeira basin (Barthem et al., 2017).

4.2 | Influence of the hydrological cycle on fisheries

The present study results indicate a seasonal pattern with productivity tending to increase as river levels decrease. This reflects the migratory behaviour of the species targeted by the region's commercial fisheries. During the flood, most of fish species migrate to the forests to utilise flooded areas to get shelter, food and breeding opportunities (Junk, Soares & Saint-Paul, 1997). In this period, the fish are widely dispersed and it hampers fishing efforts (Cardoso & Freitas, 2007; Doria et al., 2012; Goulding, 1979) resulting in decreases in fishing colony landings. As the river level begins to lower (ebb), the migratory species begin to form shoals and begin their dispersal migration (Barthem & Goulding, 2007). In this period, the fishermen utilise the movement of the shoals to catch them. At low water, many lakes become extremely shallow and many fish seek refuge in the remaining bodies of water forming major concentrations of individuals, which facilitate their capture by local fishers (Alcântara et al., 2015).

4.3 | Impacts of fluviometric changes on fisheries

The present study results indicate that the intensity of the region's fisheries is primarily determined by the hydrological cycle, which regulates the concentration of fish in the water (Isaac & Barthem, 1995). Consequently, the stability of the flood pulse is fundamental to the maintenance of fishery resources in the Amazon basin, and the results of the present study indicate that the dams on the Madeira River have substantial impacts on the dynamics of the flood pulse on this river. This flood pulse instability may be one of the principal factors determining the decline in fishery catches in the region. Analysis of the catch history indicated that the greatest decline in production was during the periods most affected by the increase in the mean level of the river. This result was corroborated by the linear equation analysis, which identified that for each 100 cm of increase in the river level mean after damming there was a decrease in catch of approximately 12.5% of the fishery production. This result indicates that the post-dam hydrological changes altered the ideal conditions for fishing productivity in the region. These changes in fishery dynamics may thus be related to the variation in river levels between periods (Before vs After) and may be related to two principal processes: (a) a reduction in the concentration of fish during periods of higher river levels, which hinders the capture of fish and limits fishery efforts (Goulding, 1979);

and (b) a decrease in the number of fishing trips during periods of high river level to avoid economic losses from the costs of unsuccessful excursions.

In addition to affecting the dynamics of fishery activities, a number of studies have shown that instability in the hydrological cycle generated by the construction of hydroelectric dams may alter the structure and composition of the local fish communities (Agostinho, Gomes & Zalewski, 2001; Fernandes et al., 2009; Fitzgerald et al., 2018). This may be related to the impacts on the essential ecological processes that guarantee the maintenance of fishery stocks. In particular, changes in the hydrological cycle may affect the connectivity between terrestrial and aquatic networks, which is fundamental to the maintenance of biodiversity and its intrinsic evolutionary processes (Tundisi & Matsumura-Tundisi, 2008). This is worrying because, in the coming decades, the trend of species disappearance will be significant.

The results of the present study indicate that the increase in river levels caused by damming of the river caused a delay in the ebb period. In this case, the dispersal of the migratory species that depend on falling river levels to initiate their migrations (Ribeiro & Petrere, 1990) will also be delayed, which may reduce the possibility of their capture during this period. This indicates that the Santo Antônio and Jirau dams may alter the periods of migration and spawning of the fish of the Madeira River. Dams may influence the migratory behaviour of fish by interrupting essential hydrological signals, which the species have responded to systematically over periods of many thousands of years (Anderson et al., 2018). This may account for monthly peak fishery catches shifting from July/August, in the ebb period, to September/October (low water) after damming and indicates a delay of 2 months in the migration of the fish of the Madeira River. This would also account for the reduced loss of productivity in October, with catches being sustained by late migrations.

5 | CONCLUSIONS

The results of this study indicate that the dams constructed on the Madeira River have two distinct types of impact on the region's fisheries. The first type of impact is related to the direct effects of the changes in the environment on the local fish communities, such as the blocking of migratory routes. The second type of impact is linked to the influence of environmental changes on the dynamics of fishery activities, such as a reduction in capture success. The influence of the Santo Antônio and Jirau dams on the decline in the fisheries of the Madeira basin highlights the high price paid by local populations for the environmental impacts caused by the development of the hydroelectric potential of the Amazon basin. This emphasises the need for consistent and impartial environmental management strategies that guarantee the mitigation of these impacts or compensate for the damage caused to the commercial fishers and the local fish diversity.

Finally, it is recommended that:

1. The fish catch be continuously monitored through the creation of a database of the main Madeira river fishing colonies both upstream and downstream of the dams. These data will able to support future evaluations of the basin's fisheries.
2. A technological program development be established for fish reproduction in the basin to enable the repopulation of species affected by hydroelectric dams.
3. Both the concessionaires responsible for the dams and the government agencies invest in the diversification and strengthening of local livelihoods and repair known social problems.
4. The fisheries management be considered with greater importance in the environmental licensing processes to reduce the socio-environmental impacts caused by the construction of new hydroelectric plants.

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REFERENCES

Agostinho, A. A., Gomes, L. C., Veríssimo, S., & Okada, E. K. (2004). Flood regime, dam regulation and fish in Upper Paraná River: Effects on assemblage attributes, reproduction and recruitment. *Reviews in Fish Biology and Fisheries*, *14*(1), 11–19.

Agostinho, A. A., Gomes, L. C., & Zalewski, M. (2001). The importance of floodplains for the dynamics of fish communities of the upper river Paraná. *Ecohydrology and Hydrobiology*, *1*(1), 209–217.

Agostinho, S. A., Miranda, L. E., Bini, L. M., Gomes, L. C., & Thomaz, S. M. (1999). Patterns of colonization in Neotropical reservoirs and prognosis on aging. In J. G. Tundisi & M. Straskraba (Eds.), *Theoretical reservoir ecology and its applications* (pp. 227–265). Rio de Janeiro, Brazil and Leiden, The Netherlands: Backhuys Publishers.

Agostinho, A. A., Pelicice, F. M., & Gomes, L. C. (2008). Dams and the fish fauna of the Neotropical region: Impacts and management related to diversity and fisheries. *Brazilian Journal Biology*, *68*(4), 1119–1132.

Alcântara, N. C., Gonçalves, G. S., Braga, T. M. P., Santos, S. M., Araújo, R. L., Lima, J. P., … Oliveira, A. T. (2015). Avaliação do desembarque pesqueiro (2009-2010) no município de Juruá, Amazonas, Brasil. *Biota Amazônia*, *5*(10), 37–42.

Almeida, O. T., Lorenzen, K., & McGrath, D. G. (2004). Commercial fishing sector in the regional economy of the Brazilian Amazon. In R. Welcomme & T. Peter (Orgs.), *Proceedings of the Second International Symposium on the Management of Large Rivers for Fisheries* (pp. 15–24). FAO-Regional Office for Asia and the Pacific/Publicación RAP, vol 2. Bangkok, Thailand: Editora.

Anderson, E. P., Jekins, C. N., Sebastian, H., Ocampo-Maldonado, J. Á., Carvajal-Vallejos, F. M., Encalada, A. C., … Tedesco, P. A. (2018). Fragmentation of Andes-to-Amazon connectivity by hydropower dams. *Science Advances*, *4*(1), 1429–1437.

Araujo-Lima, C. A. R. M., & Ruffino, M. L. (2003). Migratory fishes of the Brazilian Amazon. In J. Carolsfeld, B. Harvey, C. Ross, & A. Baer (Eds.), *Migratory fishes of South America: Biology, fisheries and conservation status* (pp. 235–307). Ottawa, ON: International Development and Research Centre, World Fisheries Trust.

Assis, D. A. S., Dias-Filho, V. A., Magalhães, A. L. B., & Brito, M. F. G. (2017). Establishment of the non-native fish *Metynnis lippincottianus* (Cope 1870) (Characiformes: Serrasalmidae) in lower São Francisco River, northeastern Brazil. *Studies on Neotropical Fauna and Environment*, *52*(3), 228–238.

Barthem, R. B., & Goulding, M. (2007). *Um ecossistema inesperado: A Amazônia revelada pela pesca*. Belém, Brazil: Amazon Conservation Association (ACA), Sociedade Civil Mamirauá. 241 pp.

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

Batista, V. S., & Petrere, Jr, M. M. (2003). Characterization of the commercial fish production landed at Manaus, Amazonas State, Brazil. *Acta Amazonica*, *33*(1), 53–66.

Boschio, A. A. P. (1992). Produção pesqueira em Porto Velho, Rondônia (1984-89) - Alguns aspectos ecológicos das espécies comercialmente relevantes. *Acta Amazonica*, *22*(1), 163–172.

Bui, T. M. H., & Schreinemachers, P. (2011). Resettling farm households in northwestern Vietnam: Livelihood change and adaptation. *International Journal of Water Resources Development*, *27*(4), 769–785.

Bunn, S. E., & Arthington, A. H. (2002). Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management*, *30*, 492–507.

Cardoso, R. S., & Freitas, C. E. C. (2007). Desembarque e esforço de pesca da frota pesqueira comercial de Manicoré (médio rio Madeira), Amazonas, Brasil. *Acta Amazonica*, *37*(4), 605–612.

Cella-Ribeiro, A., Assakawa, L. F., Torrente-Vilara, G., Zuanon, J., Leite, R. G., Doria, C., & Duponchelle, F. (2015). Temporal and spatial distribution of young *Brachyplatystoma spp.* (Siluriformes: Pimelodidae) along the rapids stretch of the Madeira River (Brazil) before the construction of two hydroelectric dams. *Journal of Fish Biology*, *86*, 1429–1437.

Cerdeira, R. G. P., Ruffino, M. L., & Isaac, V. J. (1997). Consumo de pescado e outros alimentos pela população ribeirinha do lago grande de Monte Alegre, PA. Brasil. *Acta Amazonica*, *27*(3), 13–228.

Correa, S. B., Costa-Pereira, R., Fleming, T., Goulding, M., & Anderson, J. T. (2015). Neotropical fish–fruit interactions: Eco-evolutionary dynamics and conservation. *Biological Reviews of the Cambridge Philosophical Society*, *90*, 1263–1278.

Costa, L. S. S. (1998). *As hidrovias interiores no Brasil*. Rio de Janeiro, Brazil: Serviço de Documentaçao da Marinha, Coleçao Amigos do Livro Naval. 125 pp.

Costa-Pereira, R. V., & Galetti, M. (2015). Frugivore downsizing and the collapse of seed dispersal by fish. *Biological Conservation*, *191*, 809–811.

Doria, C. R. C., Ruffino, M. L., Hijazi, N. C., & Cruz, R. L. (2012). A pesca comercial na bacia do rio Madeira no estado de Rondônia, Amazônia brasileira. *Acta Amazônica*, *42*(1), 29–40.

Dugan, P. J., Barlow, C., Agostinho, A. A., Baran, E., Cada, G. F., Chen, D., … Winemiller, K. O. (2010). Fish migration, dams, and loss of ecosystem services in the Mekong. *Ambio*, *39*, 2677–2698.

Duponchelle, F., Pouilly, M., Pécheyran, C., Hauser, M., Renno, J. F., Panfili, J., … Baras, E. (2016). Trans-Amazonian natal homing in giant catfish. *Journal of Applied Ecology*, *53*, 1511–1520.

Fearnside, P. M. (2014). Impacts of Brazil's Madeira River dams: Unlearned lessons for hydroelectric development in Amazonia. *Environmental Science & Policy.*, *38*, 164–172.

Fernandes, R., Agostinho, A. A., Ferreira, E. A., Pavanelli, C. S., Suzuki, H. I., Lima, D. P., & Gomes, L. C. (2009). Effects of the hydrological regime on the ichthyofauna of riverine environments of the Upper Paraná River floodplain. *Brazilian Journal of Biology*, *69*(2), 669–680.

Fitzgerald, D. B., Perez, M. H. S., Sousa, L. M., Gonçalves, A. P., Py-Daniel, L. R., Lujan, N. K., … Lundberg, J. G. (2018). Diversity and community structure of rapids-dwelling fishes of the Xingu River: Implications for conservation amid large-scale hydroelectric development. *Biological Conservation*, *222*, 104–112.

Furtado, L. G. (2006). Origens pluriétnicas no cotidiano da pesca na Amazônia: Contribuições para projeto de estudo pluridisciplinar. *O Boletim do Museu Paraense Emílio Goeldi*, *1*(2), 1981–8122.

Gehrke, P. C., Gillgian, D. M., & Barwick, M. (2002). Changes in fish communities of the Shoalhaven River 20 years after construction of Tallowa dam, Australia. *River Research and Applications*, *18*, 265–286.

Goulding, M. (1979). *Ecologia da pesca do rio Madeira*. Manaus, Brazil: INPA, CNPQ-INPA. 172 pp.

Goulding, M., Barthem, R., & Ferreira, E. (2003). *The Smithsonian Atlas of the Amazon*. London, UK: Smithsonian Books.

Guyot, J. L. (1993). Hydrogéochimie des fleuves de l'Amazonie bolivienne, ORSTOM, Collection Etudes et Thèses, Paris.

Hallwass, G., Lopes, P. F., Juras, A. A., & Silvano, R. A. M. (2013). Fishers' knowledge identifies environmental changes and fish abundance trends in impounded tropical rivers. *Ecology Applications*, *23*(2), 392–407.

Holmlund, C. M., & Hammer, M. (1999). Ecosystem services generated by fish populations. *Ecological Economics*, *29*(2), 253–268.

IBGE (2017). Instituto Brasileiro de Geografia e Estatística. Retrieved from http://www.cidades.ibge.gov.br/xtras/perfil.php?lang=_EN&codmun=130170&search=amazonas|humaita

Isaac, V. J., & Barthem, R. B. (1995). Os recursos pesqueiros da Amazônia brasileira. *O Boletim do Museu Paraense Emílio Goeldi*, *11*, 295–339.

Junk, W. J. (2001). The flood pulse concept of large rivers: Learning from the tropics. *Verhandlungen des Internationalen Verein Limnologie*, *27*, 3950–3953.

Junk, W. J., Bayley, P. B., & Sparks, R. E. (1989). The flood pulse concept in river floodplain systems. *Canadian Journal of Fisheries and Aquatic Science*, *106*, 110–127.

Junk, W. J., & Mello, J. A. S. (1990). Impactos ecológicos das represas hidrelétricas na bacia amazônica brasileira. *Estudos Avançados*, *4*, 126–143.

Junk, W. J., Soares, M. G. M., & Saint-Paul, U. (1997). The fish. In W. J. Junk (Ed.), *The central Amazon floodplain: Ecology of a pulsing system* (pp. 385–408, 1st ed.). Berlin, Germany: Springer-Verlag.

Kirchherr, J., & Charles, K. (2016). The social impacts of dams: A new framework for scholarly analysis. *Environmental Impact Assessment Review*, *60*, 99–114.

Lees, A. C., Peres, C. A., Fearnside, P. M., Schneider, M., & Zuanon, J. A. S. (2016). Hydropower and the future of Amazonian biodiversity. *Biodiversity and Conservation*, *25*, 451–466.

Leprieur, F., Beauchard, O., Blanchet, S., Oberdorff, T., & Brosse, S. (2008). Fish invasions in the world's river systems: When natural processes are blurred by human activities. *PLoS Biology.*, *6*(12), 404–410.

Lima, P. K. F., Almeida, I. C., Teixeira, J. A., & Melo, R. A. (2016). A comercialização do pescado no município de Santarém, Pará. *Revista Brasileira de Engenharia de Pesca*, *9*(2), 1–9.

Lobato, T., Hauser-Davis, R., Oliveira, T., Silveira, A., Silva, H., Tavares, M., & Saraiva, A. C. F. (2015). Construction of a novel water quality index and quality indicator for reservoir water quality evaluation: A case study in the Amazon region. *Journal of Hydrology*, *522*, 683.

MME/EPE (2017). Ministério de Minas e Energia/Empresa de Pesquisa Energética. Plano Decenal de Expansão de Energia 2026 (pp. 1–271). Retrieved from http://www.mme.gov.br/documents/10584/0/PDE2026.pdf/474c63d5-a6ae-451c-8155-ce2938fbf896

Neraas, L. P., & Spruell, P. (2001). Fragmentation of riverine Fragmentation of riverine systems: The genetic effects of dams on bull trout (*Salvelinus confluentus*) in the Clark Fork River system. *Molecular Ecology*, *10*(5), 1153–1164.

Ohara, W. M., Queiroz, L. J., Zuanon, J. A., Torrente-vilara, G., Vieira, F. G., Pires, T., & Doria, C. R. (2013). O rio com a maior diversidade de peixes do mundo. In XX Encontro Brasileiro de Ictiologia 2013. Maringá, Brazil: Universidade Estadual de Maringá.

Pelicice, F. M., Azevedo-Santos, S. V. M., Vitule, J. R. S., Orsi, M. L., Lima, J. D. P., Magalhães, A. L. B., … Agostinho, A. A. (2017). Neotropical freshwater fishes imperilled by unsustainable policies. *Fish and Fisheries*, *18*, 1119–1133.

Queiroz, L. J., Torrente-vilara, G., Ohara, W. M., Pires, T. H. S., Zuanon, J., & Doria, C. R. C. (2013). *Peixes do Rio Madeira*, vol. 3, 1st ed. São Paulo, Brazil: Dialeto. 1163 pp.

R Core Team (2011). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Retrieved from http://www.R-project.org/

Ribeiro, M. C. L., & Petrere, Jr, M. (1990). Fisheries ecology and management of the Jaraqui (*Semaprochildus taenirus*, *S. insignis*) in the Central Amazonian. *Regulated Rivers and Mangement*, *5*, 195–215.

Santana, A. C., Bentesm, E. S., Homma, A. K. O., Oliveira, F. A., & Oliveira, C. M. (2014). Influência da barragem de Tucuruí no desempenho da pesca artesanal, estado do Pará. *Revista de Economia e Sociologia Rural*, *52*(2), 249–266.

Santos, G. M. (1987). Composição do pescado e situação da pesca no Estado de Rondônia. *Acta Amazonica*, *16*(17), 43–84.

Soito, J. K. S., & Freitas, M. A. V. (2011). Amazon and the expansion of hydropower in Brazil: Vulnerability, impacts and possibilities for adaptation to global climate change. *Renewable & Sustainable Energy Review*, *15*, 3165–3177.

Sokal, R. R., & Rohlf, F. J. (1995). *Biometry: The principles and practice of statistics in biological research*. New York, NY: W. H. Freeman.

Stone, R. (2016). Dam-building threatens Mekong fisheries. *Science*, *354*, 1084–1085.

Timpe, K., & Kaplan, D. (2017). The changing hydrology of a dammed Amazon. *Science Advances*, *3*, 1–13.

Tundisi, J. G., Goldemberg, J., Matsumura-Tundisi, T., & Saraiva, A. C. F. (2014). How many more dams in the Amazon? *Energy Policy*, *74*, 703–708.

Tundisi, J. G., & Matsumura-Tundisi, T. (2008). *Limnologia*. São Paulo, Brazil: Oficina de Textos. 631 pp.

Valiente-Banuet, A., Aizen, M. A., Alcántara, J. M., Arroyo, J., Cocucci, A., Galetti, M., … Zamora, R. (2015). Beyond species loss: The extinction of ecological interactions in a changing world. *Functional Ecology*, *29*, 299–307.

Ward, J. V., & Stanford, J. A. (1995). Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. *Regulated Rivers*, *11*, 105–119.

WCD (World Commission on Dams) (2000). *Dams and development: A new framework for decision-making*. London, UK: Earthscan.

Winemiller, K. O., McIntyre, P. B., Castello, L., Fluet-Chouinard, E., Giarrizzo, T., Nam, S., … Sáenz, L. (2016). Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. *Science*, *351*(6269), 128–129.

Zahar, Y., Ghorbel, A., & Albergel, J. (2008). Impacts of large dams on downstream flow conditions of rivers: Aggradation and reduction of the Medjerda channel capacity ownstream of the Sidi Salem dam (Tunisia). *Journal of Hydrology*, *351*(3–4), 318–330.

Zhong, Y., & Power, G. (1996). Environmental impacts of hydroelectric projects on fish resources in China. *Regulated Rivers: Research and Management*, *12*, 81–98. https://doi.org/10.1002/(SICI)1099-1646(199601)12:1<81:AID-RRR378>3.0.CO;2-9

Ziv, G., Baran, E., Nam, S., Rodríguez-Iturbe, I., & Levin, S. (2012). Trading-off fish biodiversity, food security, and hydropower in the Mekong River Basin. *Proceedings of the National Academy of Sciences of the United States of America*, *109*, 5609–5614.

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