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Understanding the impacts of hydropower development on people, fish and the environment on the Madeira River of Amazonia, Brazil

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Abstract
Hydropower dams, from their construction to their operation, have well-known negative impacts on riverine fish and fishing communities. Yet, they continue to be constructed in bioculturally rich places, including the Brazilian Amazon. We investigated whether two large Amazonian dams on the Madeira River have affected the livelihoods of riverine communities by carrying out 81 in-depth interviews with local knowledge holders from 11 villages. Many of the fishers (>75%) attributed changes in both the river and its fishery to the construction of the dams. However, the perceived changes (e.g., changes to the river level) varied depending on the location of their community relative to the dams. We documented an 84% decrease in fish catch and 64% decrease in income from fishing through time. These results suggest that hydropower development has compromised the income and sustenance of local fishers, leading them to adapt their behavior, which could further compromise remaining fishing stocks.

Keywords Amazon Basin · Food Security · Hydropower Development · Small-scale fisheries · Socioecological Systems

Introduction

Hydropower dam development has increased unprecedentedly in recent years, affecting some of the world's most biodiverse and culturally rich river basins (Winemiller et al. 2016). Although these dams are advertised for providing essential energy and supporting societal development, they negatively affect biodiversity and services provided by riverine ecosystems to nearby communities (Agostinho et al. 2008; Chen et al. 2023; Selfe et al. 2025). For example, dams dampen seasonal flood pulses, reducing access to floodplains and key nursery habitats for several fish species (Almeida et al. 2020); block fish movements, decreasing population connectivity or preventing individuals from completing life cycles (Pelicice et al. 2015; Hahn et al. 2022); reduce sediment and nutrient supply downstream, affecting river productivity (Winemiller et al. 2016; Latrubesse et al. 2017); and change fish communities, altering trophic relations (Liao et al. 2018).

Dams often have critical socioecological impacts that are often underestimated (Hallwass et al. 2013; Wu et al. 2019). How local communities respond to social, economic, and cultural changes due to increasing dam development is only beginning to be understood (Santos et al. 2018; Baird et al. 2021). Many riverine communities rely on fishing and agriculture for income and subsistence and have significant cultural and spiritual ties to rivers (Pearse-Smith 2012). Although some dam projects provide benefits through employment, infrastructure, and training (Sivongxay et al. 2017), in other river systems, compensatory measures are absent, and income can decrease by 50% due to fishing and agriculture losses (McKenny 2001). Dams may change fish communities and food webs, compromising fishing catches

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and reducing fish stocks directly (Santos et al. 2018; Santos et al. 2020; Yoshida et al. 2020) or indirectly by reducing the efficacy of local gears adapted to specific flow conditions (Wyatt and Baird 2007). Consequently, dams directly affect local livelihoods, decreasing food security, food sovereignty, and income, and disrupting cultural practices (Lopes et al. 2021; Lopes et al. 2024).

One approach to better understand the socioecological impacts of dams is to access the local ecological knowledge (LEK) of fisher communities (Hallwass et al. 2013; Santos et al. 2020; Baird et al. 2021). LEK accumulates through generations via cultural transmission and personal experiences with species and ecological systems (Berkes 2008; Silvano et al. 2023). Fishers, in particular, have provided essential information on fish distribution and migration (Lopes et al. 2019), diet and reproduction (Le Fur et al. 2011; Pereyra et al. 2023), and changes in abundance and composition (Hallwass et al. 2020; Castello et al. 2024). Additionally, fisher knowledge has been used to report perceived impacts and changes caused by dams, including in the Amazon River basin (Hallwass et al. 2013; Santos et al. 2020).

The Amazon River basin, the world's largest and most biologically diverse, spans over 7 million km^2 and supports roughly 2500 described fish species (Dagosta and De Pinna 2019). It also hosts myriad ethnic and local groups dependent on its aquatic environment (Hallwass and Silvano 2016; Lopes et al. 2021). The basin is heavily dammed, with hundreds of hydroelectric dams operating or under-construction, from the Andean headwaters to its lower stretches (Anderson et al. 2018; de Souza Diaz et al. 2018). Therefore, this study aimed to determine how hydropower development affects riverine communities reliant on subsistence fishing, using a case study from the Madeira River in the Brazilian Amazon. Specifically, we sought to answer the following questions based on the perception of local fishers: (Q1) What is the contribution of Madeira River fisheries to local livelihoods? (Q2) Have perceived changes in fisheries (including fishing behavior and catch) occurred since dam construction, and do they vary by fishing community location (reservoir, upstream, and downstream)? Since previous studies found differences in fish assemblages and river geomorphology upstream vs downstream of hydroelectric dams (Fencl et al. 2015; Sá-Oliviera 2015), we also expected location-based impacts on riverine communities.

Materials and methods

This study was conducted in 2014 along the Madeira River, near Porto Velho, the capital of Rondônia, Brazil. The Madeira River, a major Amazon tributary, flows over 3240 km (Santos et al. 2018) and drains a 1,420,000 km^2 basin (Bastos et al. 2006). The two operational dams, Santo Antônio (7 km upstream of Porto Velho) and Jirau (100 km upstream), began construction in 2008 (Santos et al. 2018; Fig. 1), with reservoirs filled in 2011 and 2012, and operations starting in 2012 and 2013, respectively (Santos et al. 2018; Fearnside 2014). Both were completed in 2016, each exceeding 3500 MW capacity (Fearnside 2014; Santos et al. 2018). Their drainage covers 984,000 km^2 across Brazil, Bolivia and Peru, with reservoir flooding affecting Bolivia and Brazil (Fearnside 2014).

Study Design

We selected 11 villages along 300 km of the Madeira River, spanning upstream and downstream of the dams, to assess varied impacts on fishers. Villages varied in size and proximity to the Santo Antônio and Jirau dams, but were primarily fishing communities. Each village was categorized by location: upstream, in the reservoir, and downstream of both dams (Fig. 1 and Table S1).

Ethics

In each village, we first consulted the local leader to explain the study and obtain oral authorization to interact with residents. After approval, we applied a non-probabilistic sampling approach and the snowball technique (Howarth et al. 2024) to identify expert fishers. We interviewed all expert fishers willing to participate until we exhausted leads in each community. Each fisher received an individual explanation of the study and provided oral consent. Participation was voluntary, and anonymity was ensured per the ethics protocol approved by the University of Rio Grande do Norte, Brazil (CAAE: 54294015.5.0000.5537).

Data Collection

We applied semi-structured questionnaires with 81 fishers in November 2014, at the end of the Amazon's dry season (Fig. 1 and Table S1). The questions covered three major themes: T1) fisher socioeconomic profile; T2) fishing characteristics; and T3) changes to the fishery, Madeira River and livelihoods. T1 covered questions regarding age, family fish consumption, income sources, and financial aid. T2 collected information on fishing experience (years spent fishing), attachment to fishing locations (for how long a fisher has used a fishing spot), and boat ownership. T3 explored fishers' perceptions of environmental and fishery changes, when these occurred and their possible causes. Open-ended responses were later categorized. Fishers were also asked about current fishing catches, frequency, and duration, and whether these had changed in recent years. To

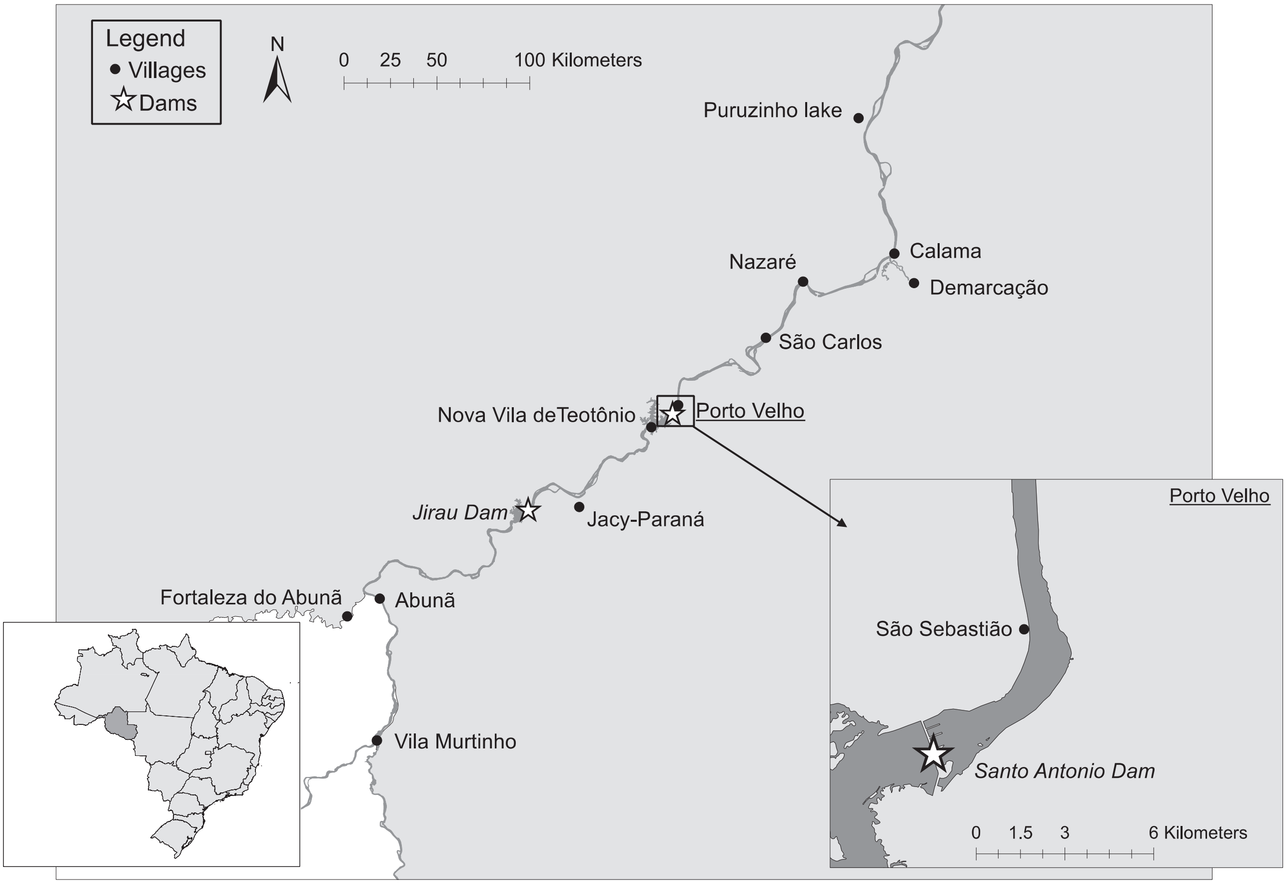

Fig. 1 Locations of the Santo Antônio and Jirau dams along the Madeira River, Brazil, and in relation to the villages surveyed in this study

understand livelihood shifts, we queried about changes in income sources and the percentage of catches sold (Table 1). While much of the data reflects fishers' subjective perceptions, shaped by multiple factors, it provides valuable insights into dam impacts on wellbeing and livelihoods. Such knowledge can inform environmental management (Bennett 2016).

Data Analyses

Contribution of Fisheries to Local Livelihoods (Q1)

We qualitatively analyzed how Madeira River fisheries contribute to local livelihoods using descriptive results from T1, T2 and T3. Averages and standard deviations were calculated for quantitative variables, with summary statistics presented for all communities together and separated by location relative to the dams.

To assess fishers' dependence on Madeira River fisheries, we created a Fishers' Reliance on Fish Index (FRI), based on social, economic, and environmental indicators of resource dependency (Marshall et al. 2007; Marshall 2011). Specifically, we used:

a. Social indicators: frequency of fish consumption (fc), and attachment to a fishing place (ap);
b. Economic indicators: current fishing income (fi), fishing as the main income source (fmi), current income sources (ci), and current proportion of catches sold (ps);
c. Environmental indicator: current fishing catches (cc).

All indicators were normalized from 0 (least dependent) to 1 (most dependent) (Table 2). Each indicator was considered equally important, and the FRI for each fisher was calculated as the average of all indicators (Silva et al. 2020).

$$FRI = \frac{[(fc + ap) + (fi + fmi + ci + ps) + cc]}{7}$$

The final FRI value was categorized into three levels of fishery dependence: low (0–0.33), moderate (0.34–0.65), and high (0.66–1) (Silva et al. 2020).

Artisanal fishers depend economically on fisheries, which often contribute between 50% and 100% of their total income (Doria and Lima 2015), while agriculture and extractivism provide additional earnings. In that sense, the

Table 1 Variable descriptions and associated categories of questions applied to fishers of the Madeira River in the Brazilian Amazon, during November 2014

Categories/Variables	Description
Fisher's socioeconomic profile	
Age	Age of a participant measured in years. Continuous variable.
Current fishing income*	Values reported in Brazilian Reais for the current fisheries earnings.
Fishing is the main income source	Binomial answers: yes or no. When answers were "yes", we collected the proportion of fishing represented in the salary.
Frequency of fish consumption	The number of times per week a fisher's family eats fish. Values were reported to a maximum number of seven (varying between 0 and 7), divided by seven and multiplied by 100 (i.e., seven days represent a complete week, thus a fisher who fishes seven times per week is fishing 100% of his/her time).
Social welfare subsidies	Any benefits or financial aids received by the fishers to help support their livelihoods, with the exception of earnings derived from formal and/or informal work and rentals. Qualitative variable.
Current income sources	Response to the questions: "Do you have another economic activity?", in case fishing was the main one; or to "What is your primary income source?", in case fishing was not the main activity. Qualitative answers.
Fishing characteristics	
Attachment to a fishing place	A response to the question: How long have you been fishing in this region? A continuous variable measured in years.
Fisher experience	Number of years a participant has been fishing since the age she/he started this activity. A continuous variable measured in years.
Own boat	In case a fisher is the owner of a boat. Binomial answers: yes or no.
Changes to the fishery, environment and livelihoods	
Perception of changes in the Madeira River	Responses to the question: What changes in the river did you notice? The answers were divided into six categories: (a) changes in river level/course; (b) dirt; (c) standing water/lakes, increasing temperature; (d) change in sedimentation and erosion; e) plants death/deforestation/falling trees; (f) fish disappearance/death/hard to fish.
Causes of changes in the Madeira River	This includes the causes of changes in Madeira River assigned by the fishers, which were later categorized into: (a) dam lake; (b) mining contamination; (c) deforestation; (d) natural causes; (e) fish migration; (f) do not know answers; and (g) other causes.
When the Madeira River changed	Quantitative responses to the question: When did you notice these changes in the Madeira River? Continuous variable.
Perception of changes in the fishery	This variable comprises qualitative data as a response to the question: What changes in the fishery did you notice? The answers were divided into eight categories: (a) fish decrease; (b) hard to fish/fishery decrease; (c) high costs to fish/decline in fishing rewards; (d) changes in gears/fishing grounds; (e) prevented fish migration; (f) fish mortality; (g) more fish; (h) other changes.
Causes of fishery changes	This includes the causes of changes in fisheries assigned by the fishers, as mentioned above, which were later categorized into: (a) dam/lake/standing water/flood; (b) overfishing; (c) fishing migration/mortality; (d) water change/contamination; (e) do not know answers; and (f) other causes.
When the fishery changed	Quantitative responses to the question: When did you notice these changes in fisheries? Continuous variable.
Fishing catches	Values reported in kg/week of current and past catches. Continuous variable.
Fishing duration	A continuous value as a response to the question: How long does the fishing take? Values were reported in the number of days for current and past fishing activities.
Fishing frequency	The number of times per week a fisher engages in a fishing activity. Values were reported for current and past frequencies to a maximum number of seven and divided by seven (i.e., seven days represents a complete week, thus a fisher who fishes seven times per week is fishing 100% of his/her time).
Changes in income sources	This variable includes responses to the question: Did your income sources change in the last few years? Binomial answers: yes or no.
When income changed	Quantitative responses to the question: When did your income sources change? Continuous variable.
Past fishing income*	Values reported in Brazilian Reais for the fisheries earnings in past times. For this variable, we did not collect data on when the changes in the generation of such income occurred.
Percentage of catches sold	Values of current and past percentage (%) of all catches a fisher sells. Past percentages represented a five-year period until the interview was conducted.

*We consider the value of R$ 724.00 (R$ 1.00 = US$ 0.37, January 2015) as the Brazilian minimum wage, which was the operative value at the time this research was conducted (2014/2015). Income calculations were based on this value

Table 2 Indicators and associated assumptions included in the Fisher reliance on fish Index (FRI). The table also describes key data treatment procedures

Component	Indicators	Assumptions	Data treatment
Social	Frequency of fish consumption	The more frequently the consumption of fish by a family in a week, the greater its importance as a source of protein. Also, usually low-income fisher families consume part of their catches in their meals and thus avoid spending money buying other types of meat. Either way, we assume that fishers' dependence is higher when they consume fish more days in a week.	We grouped the frequency a family eats fish in a week into three frequency categories: High frequency = 1 (6 to 7 days/week) Moderate frequency = 0.5 (3 to 5 days/week) Low frequency = 0 (0 to 2 days/week)
	Attachment to a fishing place	Fishers who maintain a strong relationship with a specific fishing place may experience a sense of belonging to that spot and can be significantly distressed if they are forced to fish elsewhere (Marshall 2011) due to environmental changes caused by the dams. Thus, we assume that the longer the time a fisher spends fishing in a specific place, the more attached to the place he/she is, and consequently the higher his/her dependence on the natural resource.	This variable represents the length of time a fisher has been fishing at a particular place. We normalized the data by assigning 1 point to the highest reported length in a particular fishing place. Then the other values assigned were proportionally calculated until the 0 point was reached.
Economic	Current fishing income	Successful fishers in terms of income are usually considered those who are better at exploiting fisheries resources (Marshall et al., 2007). Nevertheless, fishers who earn bigger amounts of money through fishing may be highly specialized and dependent on it as their unique income option. In this case, they are prone to suffer significant financial losses from fluctuations in fisheries resources.	All income values were normalized from 0 (lowest income value) to 1 (highest income value). R$ 6000.00 = 1 point R$ 0.00 = 0 point
	Fishing is the main source of income	We assume that fishers whose main activity to generate income is fishing are strongly dependent on their occupation. Therefore, they may lose both part of their self-identity and a means of earning income (Marshall et al., 2007) when they face environmental changes in the river.	Yes = 1 No = 0
	Current income sources	If fishers are engaged in different income activities, they possibly cope more easily with changes in the river and the fish resources because they possess other means to generate income. Thus, we assume fishers are highly dependent on fishing once this is their unique income source (Silva et al., 2020).	We normalized the number of income sources a fisher is engaged in by assigning a proportional score to each fisher, ranging from 1 (the least amount of income sources) to 0 (the greatest amount of income sources). No income sources = 1 point 3 income sources = 0 point
	Current proportion of catches sold	In this study, we assume that fishers who sell a greater proportion of their captures are more economically dependent on the fishing trade. On the other hand, those fishers who sell smaller proportions of their catches are often engaged in other income generation activities to improve their livelihoods and thus might be considered less dependent on fish (Keppeler et al., 2020).	The percentages given in this variable were normalized from 1 (the greatest proportion of catches sold) to 0 (the least proportion of catches sold). 95.5% = 1 point 0.0% = 0 point
Environmental	Current fishing catches	Fishers who catch great amounts of fish per week may benefit from better financial returns if they sell their catches, or from greater food availability if they do not. However, even though fishers who capture fewer fish might suffer severe consequences from the changes in fish stocks, we assume that fisheries dependence is higher for those fishers who capture more fish because they are probably engaged in fisheries only (Keppeler et al. 2020).	Data from fishing catches (in kg) was normalized to reach values from 1 (the greatest amount of fishing catches) to 0 (the least amount of fishing catches). We assigned proportional scores to the intervals. 700 kg = 1 point0.0 kg = 0 point

five economic indicators in the FRI index reflect this dependence but do not exclude the influence of social and environmental variables on fishers' perceptions.

Perceived Changes in Fisheries, River, and Livelihoods After Dam Implementation (Q2)

We used qualitative and quantitative approaches to analyze perceived changes in the Madeira River, fisheries, and livelihoods due to the dams. First, we recorded qualitative fisher answers on changes in the river and fisheries (T3). These responses were categorized into six types of river changes (i.e., altered river level/course; pollution or algal blooms; standing water/lakes, temperature increases; sedimentation shifts; plant death/deforestation/falling trees; fish disappearance/death/hard to fish), and eight fishery-related changes (i.e., fish decrease; hard to fish/fishery decrease; increased fishing costs; declines in fishing rewards; altered gears/fishing grounds; prevented fish migration; fish mortality; more fish; and other changes) (Table 1).

To compare perceived changes across locations (upstream, reservoir, and downstream), we ran multivariate analyses. We excluded São Sebastião village because its residents fished both in the reservoir and downstream, which could obscure location-based differences. We ran a nonmetric multidimensional scaling (NMDS) analysis using the Bray-Curtis distance and randomization (1000 permutations), followed by a similarity analysis (ANOSIM), with regions as factors. A similarity percentage analysis (SIMPER) identified key perceived changes in the river and fisheries among locations. Each community was treated as a replicate, and we calculated the proportion of perceptions within each. We used the PRIMER 6 software program (Clarke and Gorley 2006) for NMDS, ANOSIM, and SIMPER analyses.

To further understand fishery changes (T3), we performed generalized linear mixed models comparing response variables over time and across locations. Variables included: catch (kg/week), fishing duration (days per trip), fishing frequency (days per week), proportion of catches sold, and fishing income (R$/month). If respondents provided value ranges, we used the median. Predictor variables were time (current vs past; "current" refers to at the time of the interviews), location (upstream, downstream, or reservoir), and their interaction. Village was included as a random variable to account for within-village similarities. GLMMs were run using the *glmer* function in the *lme4* package (Bates et al. 2015) in R version 4.0.5 (R Core Team 2021). Catch, income, frequency, and duration models used a gamma distribution with a log link (one zero value was removed from income and catch models to enable analysis). For the proportion of catches sold, we converted reported percentages into a proportion (0-1) and used a zero-inflated beta regression (due to multiple values of 0) via the *gamlss* package (Rigby and Stasinoloulos 2005). Contrasts between groups were analyzed with *emmeans* function and package (Lenth 2018), and variables were plotted using *ggplot2* (version 3.3.3; Wickham et al.2016).

Ethical Approval

This study involved Human Participants, according to a protocol approved by the Ethics Committee at the University of Rio Grande do Norte, Brazil (CAAE: 54294015.5.0000.5537). Fishers were informed that their participation was optional and were given all information about the study prior to their agreement to participate.

Results

Importance of Madeira River's Fisheries to Local Livelihoods (Q1)

Madeira River fishers ($n = 81$) were typically middle-aged (49.6 ± 11.4 years old) males (95.1%) with 31.9 ± 12.4 years of fishing experience. They had been fishing in the same region for 26.7 ± 11.4 years, and most (95.1%) owned a boat. Their families consumed fish 4.1 ± 2.3 days per week, and fishers sold on average $77.3\% \pm 31.1\%$ of their catches (Table 2). Fishers took trips that were 4.5 ± 4.5 days long, with a frequency of 3.5 ± 2.4 days/week, and with catches of 93.1 ± 127.7 kg/week (Table S2).

Most fishers (76.5%) relied on fishing as their primary income, with other sources including agriculture, mining, government, and temporary work. Nearly all (92.6%) received social welfare subsidies, particularly the Closed Fishing Season Insurance (65.4%) and Family Allowance (37.0%), which is a cash transfer program for low-income earners. Fishers' retirement (17.3%) also contributed greatly to local livelihoods.

Considering all fishers together, the average FRI was 0.44 (range: 0.12–0.74). Most fishers had a moderate FRI (76.5%), while 19.7% had a low FRI, and only 3.7% had a high FRI. Jaci-Paraná village, located between the dams, had the highest FRI (0.74). Across locations, most fishers exhibited moderate FRI (72.7% upstream, 66.7% reservoir, and 82.9% downstream), indicating moderate fishery dependence (Table S3).

Fishers Perceptions of Changes in the River and Fishery After Dams (Q2a)

Almost all fishers (92.6%) reported changes in the Madeira River, such as altered water level, temperature, and course, with changes perceived 3.0 ± 1.4 years prior to interviews

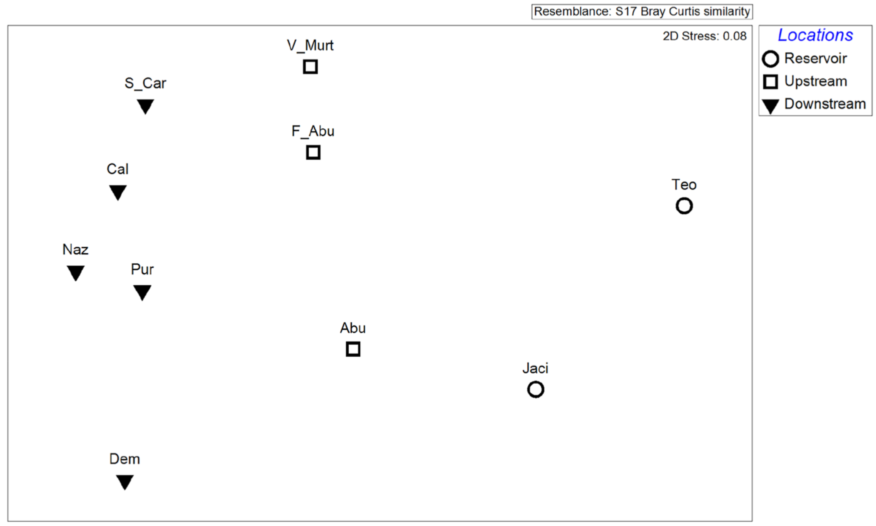

Fig. 2 NMDS ordination (stress 0.08) plot based on the citations (in percentages) of fishers' perceptions about changes in the Madeira River and its fishery for each community. Communities were considered replicates in this analysis, and location in relation to the dams (upstream, reservoir and downstream) was treated as a factor in the analysis. The plot shows high similarity in perceptions within locations (upstream, reservoir, and downstream), but differences between the locations, indicating a spatial effect on fishers' perceptions about changes to the river and fishery

(2014). Most fishers (71.6%) attributed these changes to the dams, while others cited deforestation (2.5%), mining (2.5%), and natural causes (3.7%). Additionally, 93.8% noted declines in fish and increased fishing difficulty, with changes occurring 3.6 ± 2.0 years prior to the interview. Many (60.5%) blamed the two dams, while others cited overfishing (6.2%), water contamination (2.5%), and fish migration mortality (4.9%).

The NMDS ordination (stress value = 0.08) showed spatial separation among regions regarding perceived changes (Fig. 2). We found that there were differences in perception between regions (Global R = 0.64, $p = 0.005$), while within-region similarity was high (upstream = 69.2%; reservoir = 65.8%; downstream = 71.5%), indicating a spatial effect on perception (Table S4).

Changes to Fisher Livelihoods Over Time and by Location (Q2b)

Most fishers (94.7%) reported declining catches 4.0 ± 2.5 years prior to the interviews (Table S2). The GLMM revealed a significant ($p < 0.0001$) drop in reported catches from past (594.3 ± 1002.0 kg/week) to current values (93.1 ± 127.7 kg/week), but no difference across locations and no interaction between time and location (both $p > 0.05$; Fig. 3a). Around half the fishers reported changes in fishing frequency (51.9%) and trip duration (49.4%; Table S2). Fishing frequency showed a significant ($p = 0.02$) time-location interaction (Fig. 3b). Reservoir fishers' fishing frequency declined from 5.6 ± 2.3 (past) to 2.1 ± 1.8 (current) days per week, and their current frequency differed from that of downstream fishers (4.4 ± 2.5). Fishing duration significantly ($p = 0.005$) increased from past to current values (1.9 ± 1.8 vs 4.5 ± 4.5 days per trip), but location or interaction had no effect (Fig. 3c). There were no significant differences in the proportion of fish sold across locations or time (all $p > 0.05$; Fig. 3d). Finally, 76.5% of fishers reported a change in their income 3.9 ± 2.4 years prior to the interviews (Table S2), and there was a significant decrease ($p = 0.00019$), with past earnings (R\$ 2954.52 ± 2725.42/month, or \$$1018.80 \pm$ \$$939.80$ USD) dropping to current income (R\$ 1043.98 ± 1111.41/month, or \$$359.99 \pm$ \$$383.24$ USD; Fig. 3e). Inflation was not accounted for, meaning actual losses were even greater.

Discussion

We examined perceived changes in the Madera River and fishers' livelihoods after the construction of the Santo Antônio and Jirau dams. Most fishers attributed river and fishery changes to the dams, though perceptions varied by location. Across all communities, fishers reported longer fishing trips, declining catches, and reduced fishing income. The reported LEK from our study is important as it captures a baseline for assessing future changes to the system.

Fishers' Reliance on the Madeira River Fishery (Q1)

Madeira River fishers were moderately reliant on the fishery, with 76.5% citing fishing as their primary income and eating fish about 4 days per week. Their additional income sources (agriculture, mining, and temporary work) likely explain this moderate dependence, as reflected in the FRI analysis. While fish consumption frequency varies, studies report that annual intake in the Brazilian Amazon ranges from 31 to 161 kg per person (Isaac et al. 2015; Doria et al. 2018). In some communities, fish is eaten up to six days per week (Isaac and Almeida 2011; Isaac et al. 2015), underscoring its role as a primary

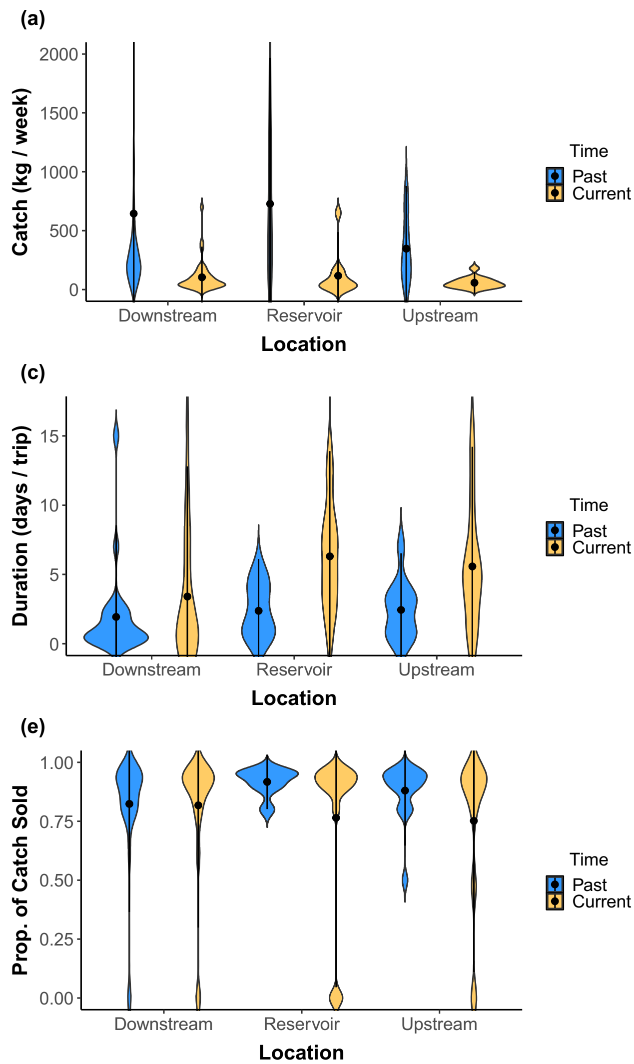

Fig. 3 Violin plots showing differences between past and current variables across locations relative to the dams. **a** Changes in fishing catch (kg per week). **b** Changes in fishing frequency (trips per week). **c** Changes in fishing duration (days per trip). **d** Changes in fishing income ($R per week); the reservoir location only has a plot for current income because there were too few data points to plot past income. **e** Changes in the proportion of fishing catch sold. Black dots and lines represent the mean and standard deviation

protein source. Our study communities align with typical small-scale fisheries in the Amazon, where fishing sustains both food and income.

Perceived Changes to the River and its Fishery Varied Based on Location Relative to the Dams (Q2a)

Nearly all fishers reported river or fishery changes, and many linked these changes to the dams. Reported river changes included altered water levels, sedimentation or erosion, deforestation, and the formation of standing water. These findings align with localized studies where fishers reported hydrological shifts, murky water, and riverbank erosion (Almeida et al. 2020; Santos et al. 2020). Perceived fishery changes included reduced fish abundance, increased fishing difficulty, higher costs, and changes in fishing gear or fishing grounds. Similarly, fishers in the Humaitá Fishers' Association, downstream of the Santo Antonio and Jirau dams, reported decreased catch, greater fishing challenges due to flooding, and an altered fish reproductive season (Santos et al. 2018; Santos et al. 2020). Another study that recorded fishers' perception in the same region 8–9 years after the dam's construction indicated declines in fishery yields and changes in catch composition both upstream and downstream (Arantes et al. 2023).In our study, the perceived changes were reported to have occurred about 3–3.5 years before our interviews (in 2014), coinciding with the Santo Antônio reservoir filling in 2011 (Fearnside 2014).

Although dam-related changes have been previously reported (Santos et al. 2018; Santos et al. 2020), our study is the first to compare and show differences across upstream, downstream, and reservoir locations. We found that fewer reservoir fishers reported river level changes than upstream or downstream fishers, but more noted standing water and deforestation (Table S4). Sedimentation and erosion were primarily reported upstream and in the reservoir. Upstream and downstream fishers mostly reported decreases in fish, while reservoir fishers reported needing to change fishing grounds and gears. Reservoir villages saw 529 km^2 of combined flooding from the dams (Fearnside 2014), likely leading to standing water, tree die-off, and permanent fish access to the floodplain, necessitating shifts in fishing practices.

Changes in Income, Catch, and Fishing Behaviors Through Time (Q2b)

Across all communities, fishers reported decreases in both catch (84%) and income (64%) from 2010 to 2014. The catch decrease was greater than the 34% decrease in monthly catch reported in the Humaitá Fishers' Association from 2002 to 2017 (Santos et al., 2018). Results may differ due to the larger sampling area (eleven communities vs one) or the differences in time period and location, as Humaitá is located over 200 km downstream of the dams. However, Arantes et al. (2022), who studied the upstream, reservoir, and downstream zones of the Madeira River, also noted a smaller decrease in catch (37%) and income (30%) between pre- and post-dam periods. Differences may be due to the fact that our interviews were conducted immediately after dam construction (2014), whereas Arantes et al. (2022) conducted interviews in 2017–2019. Finally, Doria et al. (2021) also reported changes to the Madeira River fishery after hydropower development and found that landings and revenue declined by over 50% in the capital Porto Velho, just downstream of the Santo Antônio dam. In other river systems in the Amazon, fishers have similarly reported significant decreases in income and fish catch after dam construction (Hallwass et al. 2013, Castro-Diaz et al. 2018). Combined, the body of studies offer important spatial and temporal insights into fisheries changes.

Notably, the decreases in catch and income reported in our study affected fishers regardless of their location relative to the dams. This is significant, as fishing was reported as the primary income for many of these fishers, and many families eat fish several days per week. Decreases in catch and income threaten both fishers' livelihoods and food security. Dams have been identified as a significant threat to the food security of small-scale subsistence fishers in the Amazon (Begossi et al. 2018). When access to fish is reduced, it may cause individuals to rely more heavily on nutritionally poorer foods, such as processed foods, sourced from further away (da Silva and Begossi 2009, Begossi et al. 2018, Lopes et al. 2024). Fishers may also have to choose between selling their fish or eating it, although in our study, we did not see any change in the percentage of fish sold before and after dam construction, suggesting the use trade-off was likely not occurring in our study communities.

Finally, the fishers along the Madeira River reported changes in their fishing behavior in response to the dam construction. Across all studied communities, fishers increased fishing trip duration from 1.9 days to 4.5 days, likely due to the increased effort needed to catch fish. This result accords with the high number of fishers reporting more difficulty fishing following hydropower development (Table S4). Fishers may also have to travel farther to reach suitable fishing grounds to compensate for the local reductions in catches, although we did not quantify this in our study. Similarly, Arantes et al. (2023) reported an increase in the time spent traveling to fishing grounds in the upstream region. In the same study, more than 70% of the fishers also reported spending more time fishing after dam construction. This pattern has been shown consistently across basins. For example, after the damming of the Xingu River in northern Brazil, fishers reported having to travel much farther to catch fish, and, despite this additional effort, they still caught fewer fish than before (Castro-Diaz et al. 2018). In addition to the increases in fishing duration, fishers on the reservoir decreased fishing frequency from 5.3 to 2.1 times per week. These fishers were the most impacted by the flooding and may have experienced changes in access to fishing grounds. Reservoir fishers also reported the longest duration of fishing trips, so these fishers may have switched to fewer, longer trips, especially if longer travel was required to access flooded regions. Such increases in fishing effort are a common response to the declining fish catches associated with hydropower development (e.g., Friend et al. 2009).

Caveats and Potential Biases

One important caveat is the potential negativity bias, whereby adverse events disproportionately influence the characterization of perception (Hilbig, 2009). Because our study relies on reported perceptions of river changes, negative circumstances related to the dam construction and operations could be overrepresented relative to positive ones. To minimize the influence of recent negative memories, respondents were explicitly invited to report both positive and negative changes, thereby encouraging a more balanced recall of experiences. For example, the cross-location comparisons in our study help distinguish location-specific effects from generalized perceptions. While all communities experienced hydropower-related changes, the nature and magnitude of impacts varied considerably by location.

The data for this study were also collected two years following the first operation of the dams (6 years after construction started), so the perceived negative impacts may be higher here due to the short timeline post-construction and operation. As discussed earlier, some studies that have collected data several years after dam operation (2017 and 2019-20) have still found decreases in catch and income, but to a lesser degree than in this study (Santos et al., 2018; Arantes et al. 2022 and 2023). These differences could indicate that the impacts from the dams have lessened or stabilized since the first few years post-construction, and that mitigation is needed most in the first few years post-construction. Nevertheless, further studies are needed to reassess impacts and confirm any temporal trends, since it has now been more than a decade post-construction and operation of the dams.

Finally, the data reported here on perceived decreases in fish and fish catch refer to the fishery as a whole and do not distinguish among species. We therefore do not assess differential impacts according to migratory behavior. Although migratory fish are expected to be more strongly impacted by dams than non-migratory species (Agostinho et al. 2008; Pelicice et al. 2015), our analysis does not permit the identification of species-specific differences. Accordingly, both the degree of impacts and the causes of decline likely differed with migratory status and other life-history traits of the fish species. Notably, the Upper Madeira fishery relies heavily on large migratory catfish species of the genus *Brachyplatystoma*, such as dourada and filhote (Doria et al. 2012 and 2016). As these species are the most economically valuable in the region, population declines may disproportionately influence perceptions of overall fishery decline by directly affecting fishers' income, as reported by Arantes et al. (2022).

Conclusions and Recommendations

Based on interviews of key informants engaged in community-based fisheries, our results indicate that hydropower development along the Madeira River has had significant impacts on local riverine communities. Changes to river level, flooding, and a reduction in fish have threatened the income and food security of local fishers. Our results suggest that the location of communities in relation to the dam can have an impact on the perceived changes in the river and on the fishing behaviors of local residents. There is a need to identify the characteristics of hydropower developments that maintain ecosystem services and biodiversity to inform future hydropower development (Twardek et al. 2022). In the case of the Amazon basin, future hydropower development is anticipated to yield similar or worse impacts to those documented here, particularly if environmental and local socio-economic and cultural impacts fail to be considered in discussions about trade-offs and given that hydropower development is rarely the sole environmental impact in the region (it is often followed by deforestation, mining, etc). The issues raised here, including the fact that impacts may vary over time and space, should be accounted for and mitigated in the pre-development process to ensure that hydropower evolves into an activity that is sustainable for both the environment and the subsistence of communities that rely on the ecosystem services provided by the watersheds being developed.

Data Availability

The datasets generated during this study are available on request.

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Compliance with Ethical Standards

Conflict of interest The authors declare no competing interests.

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