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Research article

Large-scale hydropower impacts and adaptation strategies on rural communities in the Amazonian floodplain of the Madeira River

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ABSTRACT

Understanding social and environmental impacts and household adaptation strategies in the face of expansions in energy infrastructure projects is essential to inform mitigation and interventions programs that promote well-being. Here we conducted surveys in seven communities distributed across varying degrees of proximity to a hydropower dam complex in the Brazilian Amazon along about 250 km of the floodplain of the Madeira River. Based on interviews with 154 fishers from these communities, we examine how fishers perceived changes in fisheries yields, changes in the composition of fish species, and whether and how adaptation strategies had evolved 8–9 years after the dams' construction. Most respondents (91%) indicated declines in yields after the dams for both upstream and downstream zones. Multivariate analyses revealed statistically significant differences in the composition of species yields in pre-and post-dam periods for all communities and in both upstream and downstream zones ($p < 0.001$). The composition of yields diversified after the dams, with an apparent decline in yields of species of greatest market value (e.g., catfishes *Brachyplatystoma* spp., *Pseudoplatystoma* spp., and jatuarana *Brycon* spp.), and increases in yields of a set of other smaller bodied and faster growing species (e.g., 'branquinhas' *Psectrogaster* spp., *Potamohinna* spp., and sardines *Triportheus* spp.). Both downstream and upstream fishers indicated that fishing profits decreased since the dams' construction (76.8% and 67.9%, respectively). To cope with these changes, the majority of both upstream and downstream fishers (>70%) stated they have had to devote more time to fishing after the dams were built. The time fishers spend traveling to fishing locations also increased for upstream communities (77.1%), but not for downstream communities. Thirty-four percent of the interviewees changed the gear they use to fish after the dams construction, with twice as many mentioning uses of non-selective gear, such as gillnets, and declining use of traditional fishing gears such as castnets and a trap ("covi"). Fish consumption overall decreased: fish was consumed 'everyday' before the dams, but 1–2 times per week or rarely after the dams were built. Although the species that declined were those of high economic value, 53% of fishers stated fish prices have increased overall after the dams. These results shed light on the potential challenges faced by fishers and which adaptation strategies they have evolved to maintain livelihoods since the construction of the dams.

1. Introduction

Although during the past few decades large numbers of dams have been de-commissioned in Europe and North America, hydropower development has expanded markedly in the Global South (Habel et al., 2020). Developing nations have been relying on hydroelectric dams as an affordable and ostensibly "clean" energy to power their economic goals (Moran et al., 2018). As a result, in the Amazon basin alone about

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200 dams with a generating capacity over 1 MW are in operation and more than 350 are planned (Flecker et al., 2022; Winemiller et al., 2016). As hydropower expansion ramps up, improved understanding of the consequences of dams to local peoples and what adaptation strategies they adopt in response to these impacts will be critical for mitigating the socioeconomic and ecological impacts of these projects.

A range of negative social and ecological impacts of dams have been documented globally. Dam construction disrupts river flow and alters sediment dynamics and water quality (Forsberg et al., 2017). Fish migration routes are obstructed, and biodiversity negatively affected (Arantes et al., 2019). Due to expanded aquatic habitat in newly formed reservoirs and an initial period of trophic surge, fishery production (fish yields, or biomass caught) can be at first enhanced, but yields tend to decline in the long term (Agostinho et al., 2016; Arantes et al., 2022). In addition, dam construction has been shown to affect the food systems and livelihoods of rural communities (e.g., agriculture, fisheries) as well as infrastructure (e.g., sanitation) in both rural and urban areas (Doria et al., 2017; Gauthier et al., 2019). Large numbers of people are usually displaced (Siciliano et al., 2018; Yankson et al., 2018) as observed in China where, since 1949, 12 million people have been resettled due to dams (Webber and McDonald, 2004).

These impacts generate adjustments, or adaptive behaviors, in both natural and human systems (IPCC, 2001; Moran, 2022). This process of *adaptation* (i.e., the capacity of a social-ecological system to learn, combine experiences and knowledge, and adjust responses to changing circumstances, Berkes et al., 2003), can be found in areas affected by hydropower development, and is initially grounded on large-scale technological solutions such as levees to control floods, and transposition systems built for fish (Prowse and Scott, 2008). More recently, however, scholars have been expanding this perspective to explore adaptation strategies that are put in place at local scales by social actors and institutions as a response to risk and new challenges (i.e., a process called inductive, or autonomous adaptation, Prowse and Scott, 2008; Reid et al., 2009).

Although adaptations are an essential response from communities and individuals to environmental change (Barnes et al., 2017; Berkes and Jolly, 2002), adaptations to alterations in the river systems caused by hydropower dams are not well explored in the literature. For example, governmental agencies responsible for dam regulation and operation usually overlook peoples' perceptions and adaptations to impacts (i.e., evaluations of perceptions and adaptations are not required, or not even suggested, by Environmental Impacts Assessments (EIA), or by the monitoring systems of these projects (Athayde et al., 2022; Doria et al., 2017). Likewise, although there is a growing literature that explores how hydropower changes livelihoods (e.g., Bro et al., 2018; Nguyen et al., 2016; Randell, 2016; Sivongxay et al., 2017), the adaptive strategies of fishers warrant more attention. For instance, Sivongxay et al. (2017) considered four hydropower projects in central Laos and found that the construction of roads and other infrastructure provided economic benefits that offset damages to fisheries. However, the bulk of the literature implies that livelihoods are damaged and communities near dams are made worse off (Fan et al., 2022) with no demonstration of potential adaptations used to cope with impacts (Atkins, 2020; Júnior and Reid, 2010; Nguyen et al., 2016). The utility of understanding adaptations can be illustrated by other large-scale threats such as climate change (e.g., Brondizio and Moran, 2008) for which policy makers and governments recognize that while mitigations can be slow and inadequate, peoples' adaptations are likely to bear the greatest impacts (IPCC, 2001; Reid et al., 2009). Understanding the perceptions and adaptations of affected people can inform policy interventions such as compensation measures that reflect the social costs of impacts. Enhancing capacity to adapt can enable people to respond to change, minimize the impacts, recover, and take advantage of new opportunities (Cinner et al., 2013; Grothmann and Patt, 2005). A careful evaluation of adaptation behaviors can therefore inform management strategies to respond to the rapid expansion of dams in the Global South more effectively.

Here, our aim is to understand the impacts and adaptation strategies of riverine communities in the face of large-scale hydropower projects in the Brazilian Amazon. We employed structured interviews to elicit information from individuals in communities in the Amazonian floodplain of the Madeira River with varying degrees of proximity to two mega dam projects—the Jirau and Santo Antônio dams. We ask how the construction of these dams has impacted fishing-related activities and associated livelihoods, and how fishers have adapted to changes wrought by the dams. We hypothesize that all communities—regardless of their location in relation to the dams—experienced negative changes in fishing-related livelihoods and have implemented adaptations to deal with this impact. However, we expect changes and adaptations will be more evident in those communities located upstream from the dams since this zone is often under stronger influence of the environmental impacts caused by the creation of a reservoir (Arantes et al., 2019). We examined how households perceived changes in fisheries yields, and the composition of fish species in yields as well as in their fishery profits. We also investigated whether and how adaptation strategies have evolved in response to these impacts 8–9 years after dams' construction was complete. We expect that possible changes in yields and composition will be reflected in adaptations in fishing strategies (e.g., effort may have increased, and locations and gears used changed) as well as changes in fish consumption and commercialization strategies. We then contrast our results with those from a comprehensive body of knowledge that has assessed dam impacts based on fishery data (e.g., fishery landings) in the Madeira River (Arantes et al., 2022; Doria et al., 2021; Lima et al., 2020; Pinto et al., 2022).

2. Material and methods

2.1. Study area

The study was conducted in the Madeira River Basin, the largest subbasin in the Amazon (Fig. 1). In the Madeira River Basin, fishing is among the most important socioeconomic activities for the local riverine communities. Fishing involves about 3000 commercial fishermen and 5000 riverine families (Doria et al., 2012; Doria and Lima, 2015). This fishery is characterized as a small-scale fishery, which is multi-specific, and artisanal based on the use of diverse and simple fishing gears. Fishing trips are generally of short duration (lasting from a few hours to 1–4 days). The fishing fleet consists mainly of small non-motorized and motorized wooden canoes (~1000 units, storage capacity of less than 600 kg) and a few larger fishing boats (average capacity of 2500 kg) (Doria and Lima, 2015). The importance of fishery for the families in the riverine communities is emphasized by the high average fish consumption estimated as 0.5–1.0 kg per capita per day. This importance is also highlighted by a high monthly fish landing per family estimated to be, on average, 369 ± 405 kg. From this production, 13% is designed to family consumption and 87% is commercialized. The income obtained from fish commercialization represents 50–100% of the average income of a riverine family (US$ 507 ± 522 in 2009), with the remaining income being derived mostly from small-scale agriculture (Doria et al., 2016).

The fisheries and governance systems in the Madeira River have been affected by the construction of the two large hydropower dams, Santo Antônio and Jirau (Fig. 1) that were completed in 2011 and 2012 (Doria et al., 2018, 2021). Santo Antônio and Jirau, with production capacities of 3568 MW and 3750 MW, respectively (Cella-Ribeiro et al., 2017), expanded the flooded area by 78% (576 km^2) and submerged riparian forests (Cochrane et al., 2017). After the construction, the physical-chemical conditions of the river and its tributaries changed (Almeida et al., 2019). These impacts in turn affected fish assemblages and fisheries, with declines in catches and total production (Arantes et al., 2022; Cella-Ribeiro et al., 2017).

Our study encompassed 7 communities distributed across ~250 km

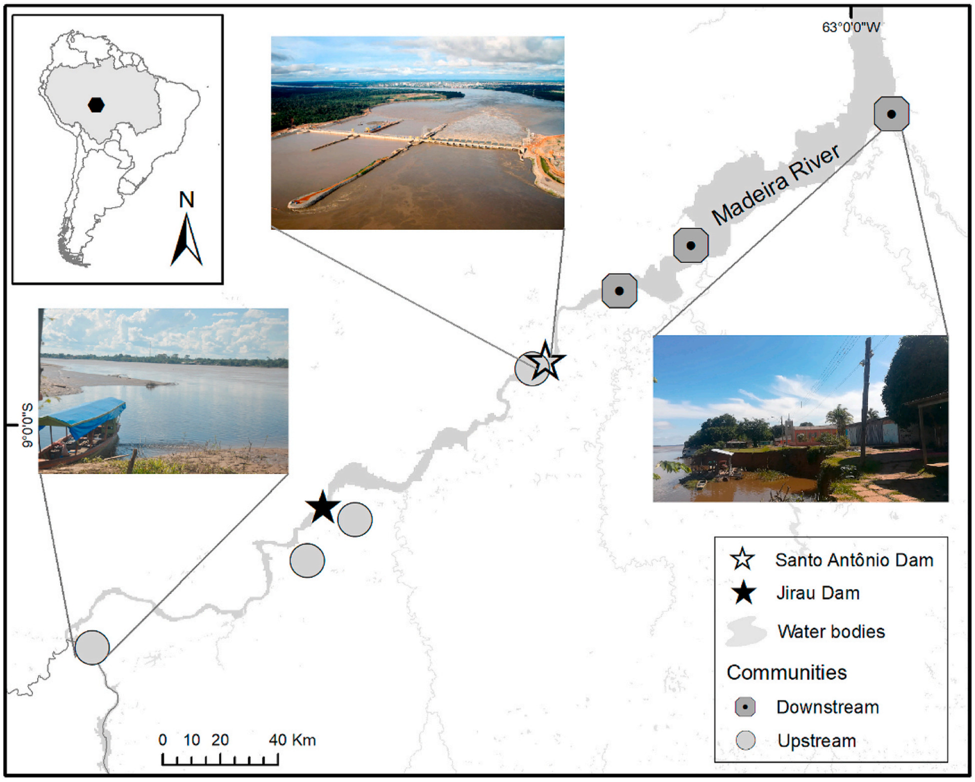

Fig. 1. Study area with indications of the seven studied communities distributed across downstream and upstream zones, and the dams Santo Antônio and Jirau, in the floodplain of the Madeira River in the Brazilian Amazon. The insert on the left shows the location of the Madeira River in the western region of the Amazon. The images highlight two communities: Abunã–upstream to the dams, and Calama–downstream to the dams. The aerial view shows the Santo Antônio dam.

in the river in downstream and upstream zones in relation to the dams (Table 1). The upstream communities are distributed between the districts of Abunã and Porto Velho, and the downstream communities between the districts of Cujubim Grande and Calama. Communities located in both zones are engaged in fisheries, but also in a range of other activities with upstream communities tending to have a more diversified economy. Two of the upstream communities, Nova Mutum and Riacho Azul, were resettled due to the construction of the dams. Riacho Azul mainly relies on agricultural production. Residents of Vila Jirau, Abunã, and Nova Mutum, the other resettled community, have also been engaged in a diverse range of temporary jobs and activities such as agriculture (e.g., farm, cattle ranching), gold mining, logging, or work as civil servants (Mayer et al., 2022). Downstream communities' occupations dates to ~1750 and none of them have been resettled. Downstream residents also engage in different activities (small-scale agriculture, government jobs, mining, and largely on fisheries), but all communities have a strong connection with the river e.g., main access to São Carlos and Calama is via boat.

Table 1
Number and percent of households interviewed in each of the 7 communities in the Madeira River. Number of interviewed in each community that identified fishing as one of their primary economic activities are indicated. The zone of location (downstream/upstream) of each community is also shown.

Zone/Communities	Number	Percent
Upstream		
Abunã	13	8.44
Riacho Azul	15	9.74
Nova Mutum	4	2.60
Vila Jirau	2	1.30
Downstream		
Calama	63	40.91
Cujubim Grande	20	12.99
São Carlos	37	24.02

2.2. Data collection

To understand perceptions of local communities on fisheries impacts and possible adaptation strategies adopted after the construction of the dams we use data from interviews conducted between August 2019 and March 2020. The initial sampling strategy was based on satellite imagery of each community with visible structures that resembled homes assigned a number. From these numbers, we derived a proportional to size random sample for each community. Interviewers used up to five contact attempts per household and were provided with a list of alternative homes if a structure was unoccupied, misclassified (i.e., it was a business), or if they were unable to make contact. The primary questionnaire was applied to about 670 households and had up to 500 questions and could take up to 1.5 h to complete—yet many questions were nested within others via skip patterns, so few respondents needed to answer all questions. The questionnaire addressed a series of socio-economic questions (e.g., questions to address engagement in participatory mechanisms provided by the dams builders, Mayer et al., 2022). For those households that identified fishing as one of their major economic activities in either or both periods, before and after the dams' construction, the questionnaire also included a set of questions that were the focus of this study.

One-hundred and fifty-four respondents in the seven communities identified fishing as being one of their primary economic activities in either or both periods, before and after the dams (Table 1), and thereby answered the supplementary fishing questions. Lower numbers of respondents in upstream compared to downstream communities (average of 6% and 25% of the households, respectively) resulted that residents of upstream communities were largely engaged in activities other than fishery. In addition, although not assessed here, as observed in other regions (Fan et al., 2022), dams impacts and displacement and resettlement of peoples at upstream zones may have increased emigrations processes of individuals that used to be largely dependent on fisheries as one of their primary economic activities.

We evaluated perceptions of respondents on impacts including potential changes in fishery production, species composition, and profits. We asked if yields and profits have declined, remained the same, or increased after the dams. Interviewees were also asked to cite the most common fish species in catches before and after the dams and to list the species they perceived had declined in abundance.

Second, we assessed possible adaptations adopted as a response to impacts. We assessed potential changes in fishing effort by asking if the travel time to fishing spots and the amount of time spent fishing had increased, decreased, or stayed the same. We also evaluated potential changes in fishing gear, household consumption of fish (both quantity and species), and commercialization strategies (i.e., species commercialized and the market price for fish).

Although the use of interviews is well recognized as a means to assess natural resources as well as human behavior, beliefs, and experiences, survey results drawn from groups of peoples may be biased towards their preconceived notions, prospects, and views, among other factors (Alshenqeeti, 2014; Kura et al., 2017). To understand potential influences of these sources of bias, we discuss our results in light of results from previous studies developed in the same study area. For example, based on fishery data collected from fishers on a daily basis, in a companion paper Arantes et al. (2022) explored how dams affected the compositions of fishery yields and monetary value of yields. We thus discuss degree of consistency among the outcomes of these analyses and our findings for a better understanding of potential challenges faced by fishers since the construction of the dams using two different data collection methods.

2.3. Data analyses

2.3.1. Impacts

We assessed possible changes in fishery yields and fishing profits based on chi-square tests comparing the frequency in classes of responses (decline, remained the same, or increased). We also compared the frequency of responses among communities distributed upstream and downstream zones based on chi-square to understand whether responses potentially differ among these zones. We assessed the number of times that a species was reported as declined to evaluate the most frequently declining fish species. Permutational Multivariate Analysis of Variance (PERMANOVA) with 999 permutations was used to test for differences in the composition of catches between pre- and post-dams periods. A non-metric multidimensional scaling (NMDS) was used to visualize differences and similarities in the composition of catches between periods. NMDS was based on presence or absence of interviewees' citations for each taxon using Jaccard distances.

2.3.2. Adaptations

Respondents answered whether the time traveling to fishing spots, the amount of time spent fishing, frequency of fish consumption (total and weekly), amounts of commercialized fish, and the market price for fish decreased, remained the same, or increased. We displayed this data graphically and used chi-square tests to compare the frequency in classes of responses (decline, remained the same, or increased). We also used chi-square tests to evaluate differences between upstream and downstream responses. We then used PERMANOVAs and NMDSs to evaluate potential changes in consumed and commercialized species and fishing gear.

All PERMANOVAs and NMDSs for assessing impacts and adaptations were conducted at three levels: all communities and communities located at upstream and downstream zones. NMDS analyses strengths were measured based on the stress coefficient, with coefficients <0.2, 0.1 and 0.05 indicating acceptable representation, good ranking, and good representation of ranking, respectively (Khalaf and Kochzius, 2002). Analyses were performed in R v.4.0.0. Chi-square tests were computed using the *MASS* package (Venables and Ripley, 2002), and PERMNOVAs and NMDSs using the community ecology R package *vegan* (Oksanen et al., 2015).

3. Results

3.1. Perceptions of impacts

3.1.1. Changes in fishery yields and profits

Most of the respondents, regardless of the zone (over 91% in both zones), indicated declines in yields after the dams (Fig. 2a and b, $p = 0.000$ for both zones). In the downstream communities, no respondents stated that fish yields had "increased" while in the upstream communities none stated "stayed the same". There were no statistically significant differences in responses between communities across downstream and upstream zones (chi-squared = 0.152, $p = 0.927$). A majority of both upstream and downstream fishers (67.9% and 76.8%, respectively) also indicated that profits decreased since the dams were completed ($p = 0.000$ for all respondents and both zones, Fig. 2c and d).

NMDS and PERMANOVA revealed a partial overlap, but statistically significant differences, in the composition of species yields in pre- and post-dams periods for all communities and both zones ($p < 0.001$) (Fig. 3 – *Fishery yields*). The composition of yields diversified after the dams as demonstrated by the larger convex hull areas (post-dams in blue and dashed lines), particularly for upstream communities (Fig. 3 – *Fishery*

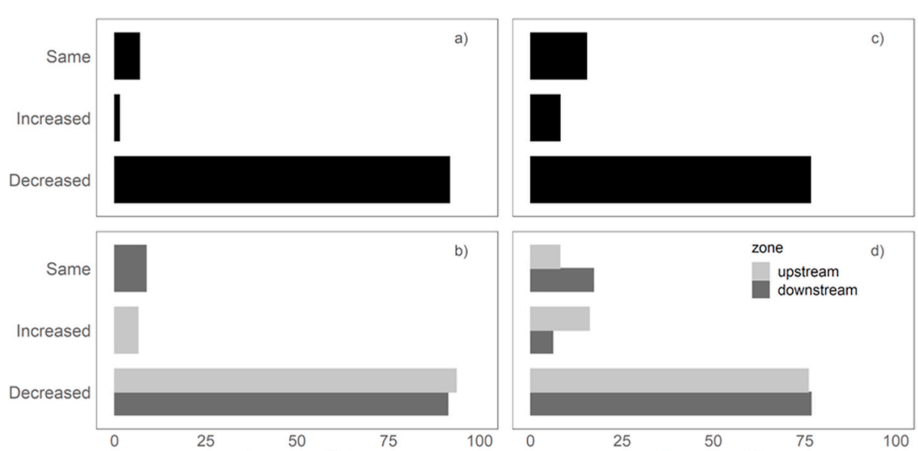

Fig. 2. Changes in fishery yields (a, b) and in fishing profits (c, d) after dams construction. Top plots (black bars) show responses of all respondents, regardless of the zone. Bottom plots (shades of gray bars) show responses of respondents according to the zone. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

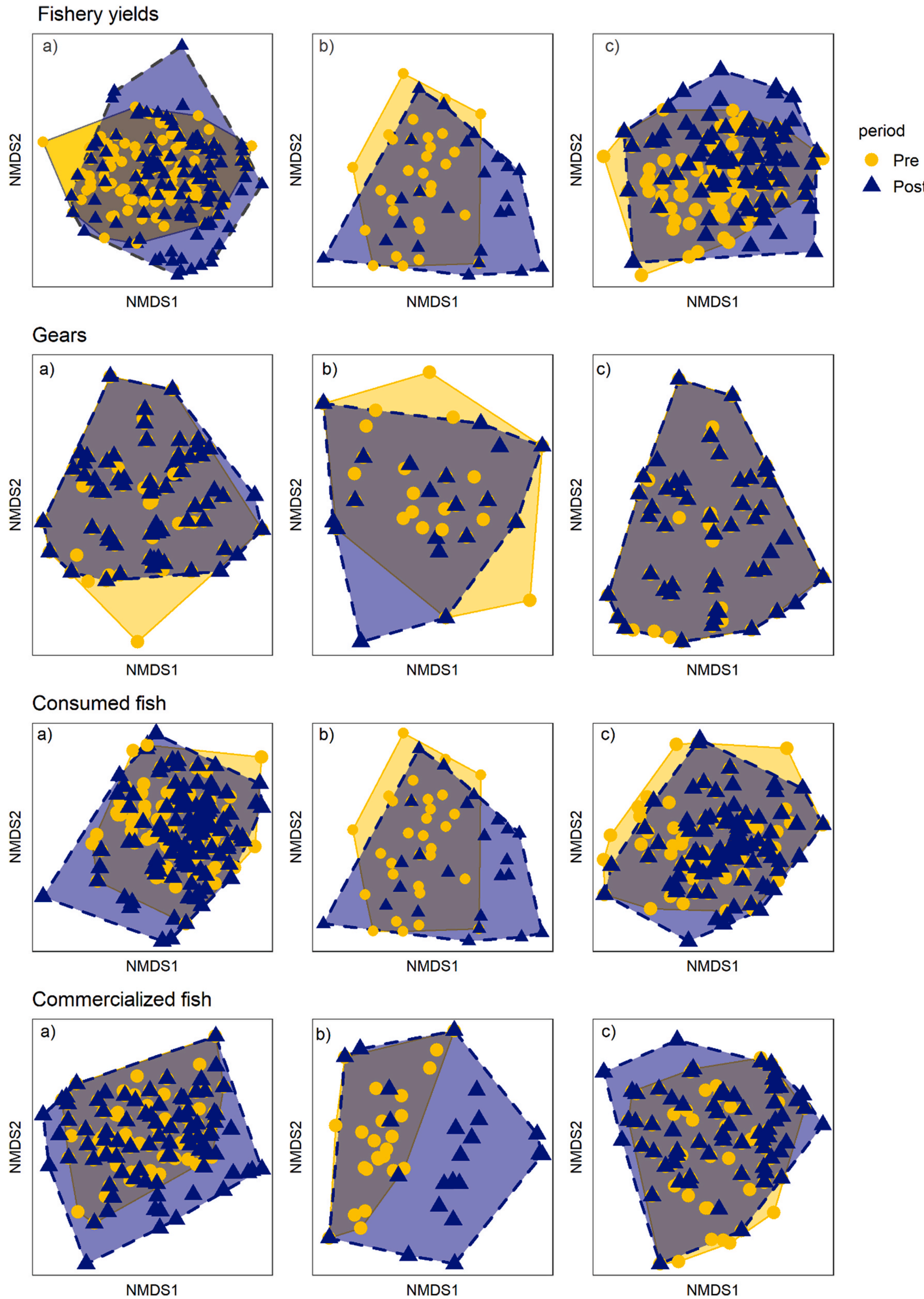

Fig. 3. NMDS results for (a) all communities, (b) upstream communities, and (c) downstream communities based on species composition in fishery yields (or, species composition in catches) (k = 3, stress = 0.12, 0.10, 0.12 for all, upstream, and downstream communities, respectively), types of gears used (k = 2, stress = 0.13, 0.09, 0.13, respectively), consumed species (k = 3, stress = 0.12, 0.07, 0.12, respectively), and commercialized species (k = 3, stress = 0.08, 0.06, 0.10). Symbols and colors represent communities in periods pre (circle, yellow) and post (triangle, blue) dams construction. Shaded polygons are convex hulls for the period pre-dams (yellow continuous lines) and post-dams (blue dashed lines). Although only the first two axes (k = 2) of the NMDS ordinations are shown here, the NMDSs for fishery yields, consumed species and commercialized species were generated with k = 3 to minimize the stress. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

yields). Across zones, goliath catfishes (*Brachyplatystoma* spp.*),* Surubins *(Pseudoplatystoma* spp.*)*, and Characids *Brycon* spp. and *Colossoma macropomum,* were more common among pre-dams catches. A set of other characids, including the species group commonly named 'branquinhas' (*Psectrogaster* spp., *Potamohinna* spp.) and sardines (*Triportheus* spp.) dominated post-dams catches. Similarities among the pre- and post-dams periods were influenced by the less frequently mentioned species in catches including Clupeiformes (*Pellona* spp.), Cichlids (acaras, e.g., *Geophagus* spp.), and Loricariids (e.g., *Pterygoplichthys pardalis*). A couple of remarkable divergences were found between zones: mentions for pirarucu (*Arapaima* spp.) in catches declined in downstream zones, but increased in upstream zones, whereas pacus (*Myleus*, *Myllossoma*) increased in downstream and declined in upstream zones. In addition to changes in composition, more than 50% of respondents indicated four species they perceived declines in yields: two Characidaes (*Bryncon* spp., *C. macropomum*) and two species of goliath catfishes (*Brachyplatystoma* spp.) (Fig. S1).

3.2. Adaptations to impacts

3.2.1. Fishing strategies: effort and gears

Overall, fishing effort increased in post-dams period (Fig. 4a, c) ($p = 0.000$ for both variables: time traveling and time fishing). Most of the upstream residents (77.1%) indicated that travel times had "increased", while in downstream communities, the majority (64.4%) stated that the time they spent traveling to fishing locations had "remained the same" (Fig. 4a and b). Although upstream respondents experienced a greater increase in travel time than those downstream, difference between respondents across zones was not statistically significant (chi-squared = 0.468, $p = 0.791$). The majority of upstream and downstream residents stated they were devoting more time to fishing after the dams (Fig. 4c and d), with no differences between zones (chi-squared = 0.189, $p = 0.909$).

Thirty-four percent of respondents indicated that they started using different fishing gears after the dams were built. In a follow-up question, fishers reported specific gears they used in pre- and post-dams periods, with results showing a partial overlap, but consistent increases in the use of gillnets (~2 times more mentions) after the dams (Fig. 3 – *Gears*). The use of hooks also slightly increased in both zones, while long lines increased in upstream zones only. The use of castnets decreased and no use of a traditional fishing trap ('covi') was observed in the post-dams period. Differences in gear composition among pre- and post-dams periods were significative for all communities (PERMANOVA, $p = 0.026$) and upstream zones ($p = 0.013$), but not for downstream zone ($p = 0.381$) (Fig. 3 – *Gears*).

3.2.2. Fish consumption

Most of the respondents (54%) stated declines in fish consumption after the dams. The frequency of 'everyday' fish consumption decreased from, on average, 60% to 22%, for all and downstream communities and from 56% to 12% for upstream communities. Whereas fish was consumed predominately 'everyday' before the dams, fishers reported 3–4 times/week, or 1–2 times/week, or rarely after the dams (Fig. 5). Although everyday consumption clearly declined after the dams (Fig. 5), difference in citations among categories of weekly fish consumption was not statistically significant (chi-squared = 0.340, $p = 0.987$). NMDS biplots revealed overlaps but with diversification in consumed fish species after the dams (see expansion in convex hulls in Fig. 3 – *Consumed fish*). The composition of consumed species changed significantly for all and upstream communities (PERMANOVA, $p = 0.003$, $p = 0.001$), but not for the downstream zone ($p = 0.164$). Overall, patterns followed changes observed in yields, with declines in consumption of goliath catfishes, surubins and large Characids (*Brycon* spp. and *C. macropomum*) of high economic importance. Conversely, there were increases in smaller-sized characids including 'branquinhas' and sardines (*Triportheus* spp.), in addition to Prochilodontidae ('curimata' *Prochilodus nigricans*) and Anostomids (e.g., the 'aracus', *Schizodon* spp., *Rhytiodus*, *Leporinus*). Notably, a few species (e.g., arapaima) not cited as being consumed before the dams, became relevant post-dams, particularly in upstream zones.

3.2.3. Fish commercialization

Most of the respondents (74%) stated declines in amounts of fish commercialized in the market. Overall, the commercialized species also diversified after the dams, with remarkable and significant changes in all communities ($p = 0.005$) and upstream zone ($p = 0.001$) but non-significant differences for downstream ($p = 0.197$) (Fig. 3 – *Commercialized fish*). Again, we observed declines in the commercialization of goliath catfishes, surubins, and large Characids (*Brycon* spp. and *C. macropomum*) and increases of 'branquinhas', sardines, curimatas,

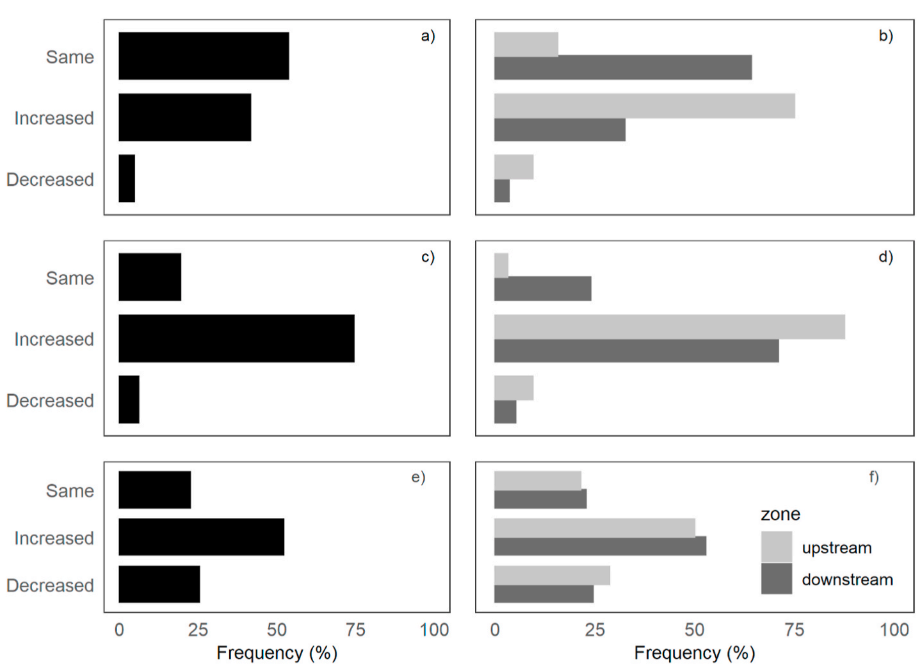

Fig. 4. Fishing effort: frequency of response for time traveling to fishing locations (a, b), time spent fishing (c, d), and trends in fish prices in the market in relation to the construction of the dams (e, f). Plots on the left (black bars) show responses of all respondents, regardless of the zone. Plots on the right (shades of gray bars) show responses of respondents according to the zone, upstream or downstream. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

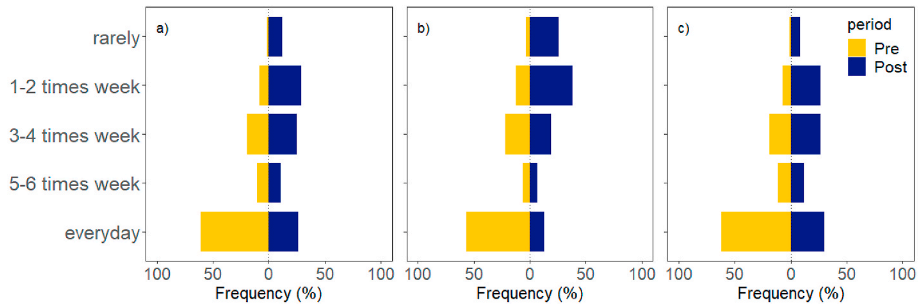

Fig. 5. Weekly frequency of household consumption of fish before (yellow) and after (blue) the dams for (a) all communities, (b) upstream communities, and (c) downstream communities. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

and Anostomids.

Although species showing declines were those of high economic value, most fishers (average 53%) stated that the price of fish increased (chi-squared = 16.10, $p = 0.000$). The difference between zones was not statistically significant (chi-squared = 0.004, $p = 0.998$) (Fig. 4e and f).

4. Discussion

Our results demonstrate that fishers experienced declines in fishery production and a shift in the composition yields after the dams, with declines of large fishes of high economic value and increases of species of low value. Consequently, fishers experienced a reduction in fishing profits. Adapting to these impacts, fishers have been spending more time fishing, with some traveling further to fishing locations. Fishers also increased the use of less selective gears such as gillnets that can target a wide range of species in the fish community. The composition of both consumed and commercialized species changed and total and weekly fish consumption declined. Although we cannot assume this result is a sole consequence of the installation of the dams, the prices of commercialized species increased in the post-dams period. These adaptive responses have been recognized within three major domains of adaptive capacity that are frequently observed at communities under stressors to their environments—assets that people can draw upon in times of need (changing in gears), flexibility (shifting species), and learning (increases fishing effort) (Cinner et al., 2018; Green et al., 2021) (see *Graphical Abstract*). Together, these results indicate that dams affected livelihoods assets and corroborate our hypothesis that the communities experienced negative changes in fishing-related livelihoods and implemented adaptation strategies to address these deleterious changes.

The declines in yields and changes in the composition are consistent with previous studies based on analyses of actual fishery yields from landings that were developed in the region (Arantes et al., 2022; Doria et al., 2021; Lima et al., 2020). Corroborating our findings, these studies showed that catch per unit effort declined after the construction of the dams—Arantes et al. (2022) found declines in yields of 37% in the Madeira River. Similarly to our results, these studies demonstrated evident decreases in species that are known to be strongly dependent on hydrological connectivity such as the goliath catfishes (*Brachyplatystoma* spp.) and on flow pulses such as *Brycon* spp. to trigger migration and reproduction (Duponchelle et al., 2021) (see Fig. 3 – *Fishery yields*). Likewise, the functional composition of fishery yields was shown to have changed in the region (Arantes et al., 2022), which supports our findings showing fishers to have perceived shifts in fish composition yields. Our results indicate that whereas large species that have regional or long-distance migratory behavior declined, composition of species in catches diversified after the dams (i.e., see expansions in the convex hull in the NDMS biplots, Fig. 3 – *Fishery yields*). This diversification of yields appears to be due to increases in abundance of short-lived, fast growing, and small bodied species (e.g., branquinhas, sardines), and/or to fishing becoming less selective. Declines in fishing profits observed by most fishers were also reported by Arantes et al. (2022), who showed dams lead to declines of on average 30% in fishing income, and 21% in the indicator of monetary value of the yields (or, the economic value of catches). Consistency among our findings and previous studies support the view that interviews with fishers can provide reliable information to assess the status of a fishery and improve understanding of how local people experience and adapt to impacts (Bennett et al., 2016; Blythe, 2015; Cinner et al., 2013; Dutka-Gianelli et al., 2022).

Despite this evidence of accuracy in the results, as pointed out by previous studies using recall methods, interviewees may not sufficiently remember how conditions were before a baseline (e.g., dam construction) which can elicit bias in the results (Kura et al., 2017). Perceptions of changes may be also underlain by a combination of drivers rather than solely by the dams. In this study, for example, fishers' perceptions of declines in yields of a fish of economic importance, tambaqui (*C. macropomum*), may be partially related to reductions in this species' yields due to a fishery moratorium that had been in place until a couple of years after the conclusion of the dams (MMA, 2005). Although our questionnaire focused on memories associated with the dams and results showed high degree of consistency with outcomes of previous analyses in the same region, we recognize we cannot tease apart the potential influences of confounding effects derived from recalling methods and other drivers of peoples' perceptions. To avoid the influences of these sorts of bias, data collection ideally should be conducted over time encompassing periods both before and after the impact. Implementing long-term data monitoring systems in association with dam development projects is thus critical for providing this type of panel data to allow better understanding of dynamic processes of changes in livelihoods.

The observed adaptations confirmed our hypothesis that communities have adapted in response to negative changes in fishing-related livelihoods regardless of their location in relation to the dams. Most fishers stated they increased fishing effort, spending more time in fishing activities as a result of observed declines in production. Time of travel to fishing locations though did not increase consistently: while most interviewers stated it increased upstream, it remained the same in downstream communities. Fishers from upstream communities may be traveling further to fish because of the large expansions (576 km^2) in the water surface—67% greater than it was foreseen in the assessment of impacts (Li et al., 2020)—that occurred in this zone after impoundment (Cochrane et al., 2017). In addition, one of the communities in the upstream zone was resettled from a riverine area to a location distant from the river. Despite those perceived impacts appeared to be greater in upstream zones, overall, increases in fishing effort imply trade-offs in fishing cost-benefits, with increases in both time dedicated to the activity and expenses with provisions (e.g., fuel, food supplies, equipment) that were not properly compensated by returns in yields and profits. These results highlight the urgent need for compensatory measures applied to communities that account for their financial and fishery losses.

That most respondents stated they used the same gears before and after the dams construction can be explained by the fact that, regardless of period and zone, gillnets have been the most used gear. Indeed, the use of gillnets in the Amazon has been widespread starting in the 1960's (Smith, 1985). Nonetheless, 34% of respondents indicated changes in their use of fishing gears, with an apparent trend to replace traditional gears that are more species-selective (castnets and traps) with non-selective gears such as gillnet and driftnet that enable higher catch rates. These results indicate that changes in the river conditions and species caused by the dams can lead to losses in traditional fishing practices affecting the cultural heritage of communities.

Declines in weekly consumption and changes in consumed fish species may be primarily a response of the patterns observed for yields (i.e., declines and changes in species in yields), but may also have been influenced by changes in households' dietary patterns due to potential alterations in the regional food system. Declines in yields may have resulted in households reducing fish consumption to favor selling their catches. Apparently, following same trends in yields, households diversified species they consume by becoming less selective towards the consumption of small-sized and lower valued species (while reducing consumptions of species of higher cultural and economic value). The reduction in fish consumption may also be a result of potential changes in consumption patterns driven by increased access to other types of foods such as processed and canned foods and food rich in fats and sugars which has been observed in regions under increasing urbanization or influences of infrastructure development projects (Godfray et al., 2010). In the Amazon, fish has traditionally been a major source of protein as demonstrated by studies showing average annual per capita consumption 4 times higher than the world's average (Isaac et al., 2015). Our results thus call for detailed research exploring the effects of dams in levels of protein intake and consequences for health and food security of local peoples.

Similarly, diversification in species commonly commercialized can be explained by aforementioned changes in yields with consistent patterns of increases in a variety of lower market-value species and declines of species of high economic values. These results can partially explain why fish prices increased: fishers may have attempted to compensate for losses in total yields (i.e., declines in fish yields that in turn lead to declines in market supply), but especially in losses of those species of greatest economic value. Obviously, increases in fish prices cannot be attributed only to the construction of dams on fisheries *per se*. Increased prices should be a combined result of the dams' impacts and multiple economic and social burdens that have caused inflation rates in Brazil to rise. Indeed, from the beginning of the construction of the dams to their conclusions (or from 2008 to 2013), fish market prices increased ~60% (Lima et al., 2020) while inflations rates rose roughly to 39.67% (IBGE, 2022, https://www.ibge.gov.br/explica/inflacao.php). Disproportional increases in fish market value compared with inflation rates thus support the idea that the dams along with other factors may have driven the increases in fish prices due to diminished supply. An important next step towards understanding of dams impacts in the fishery market should disentangle the influences of dams from other factors that can increase fish prices (e.g., changes in fisheries conditions and inflation rates).

Results showed perceived impacts and adaptations put in place by communities in both upstream and downstream zones, but that the adaptation strategies were more evident upstream from the dams. Notably, impacts and adaptations in upstream communities found here may be understated with even greater negative patterns of impacts and array of adaptations in this zone potentially not depicted in our study. Although the dams in the Madeira River were planned as run-of-the-river type of dam (i.e., with little or no capacity for storage of water inflows), as mentioned, upstream communities experienced dramatic changes in the river ecosystems such as expansion in the flooded area and changed water physical-chemical conditions (Almeida et al., 2019; Cochrane et al., 2017). These changes not only strongly affected the fish fauna (Cella-Ribeiro et al., 2017) and fisheries (Arantes et al., 2022; Lima et al., 2020), but profoundly impacted social and economic dynamics in the region (Doria et al., 2021; Pinto et al., 2022). For instance, the community of Nova Mutum was resettled in a location that is ~60 km from the river, underpinning the complex sets of challenges residents faced to continue fishing to sustain their livelihoods. Yet, although not quantitatively assessed by this study, it is possible that in response to challenges, including the increased distance to the river and fishing locations, upstream residents likely diversified their economic activities to become less depend on fisheries. In addition to these changes in livelihoods, disruptions in social relations that are commonly associated with resettlement projects (Fan et al., 2022), might have increased emigration rates from the communities resulting in adaptations that are not described in our study.

Downstream from the dams, communities did not directly experience the formation of a reservoir, but they experienced changes in flow with remarkable changes in the day-to-day and sub-daily flow variability (Almeida et al., 2020). This short-term variation in river flow as a result of dam operations, in addition to physical barriers that impede reproductive migrations, are likely affecting life cycles of several fish species at downstream zones to non-quantified scales. Yet, negative impacts on fisheries perceived by fishers in this zone (e.g., declines in yields and fishing profits) are consistent with work showing signs of declines in commercial fishing landings at a major city located ~200 km downstream to our study area (Santos et al., 2018). Overall, these results support the view that although often overlooked, hydropower projects throughout the world impact the livelihoods of people living downstream from dams (Baird et al., 2015; Richter et al., 2010). To fully understand magnitudes of impacts and array of adaptations strategies communities have applied or will apply in the long-term, it will be essential for future work to assess shifts in economic activities and track changes in livelihoods of peoples that no longer live in their original or resettled communities.

5. Conclusion

Hydropower deployment will likely continue at a rapid pace in the developing world as these nations seek a reliable, affordable energy source, independence from energy imports, and an ostensibly clean source of power to drive their economic development. In this study, we asked how changes caused by dams impacted populations dependent upon river ecosystems and how they are adapting to these impacts. The results demonstrate that communities in the Madeira River were impacted by losses in fisheries yields and profits and, in response, many households in both zones tended to increase time fishing and fish prices, reduced weekly fish consumption, adapted types of gear and shifted fish species they commercialized and consumed.

However, despite demonstrations of adaptations in fishing strategies, non-statistically significant results were observed (e.g., types of gears, and consumed species in downstream communities). These results indicate that households varied in their capacity to respond to changes (i.e., varied in their adaptive capacity). Several conditions are shown to underlie determinants of adaptive capacity including social capital (leadership, trust, reciprocity and exchange, evolution of common rules), local knowledge, acquisition of new skills, and development of alternative livelihoods (Brondizio and Moran, 2008; Green et al., 2021). Understanding differential adaptive capacity among households and communities and conditions driving this capacity is beyond the scope of this work but will be necessary to further understand the strategies to build adaptive capacity in the region. For example, the adaptation of reducing fish daily intake while a reasonable short-term strategy to deal with declining yields can lead to food insecurity and malnutrition unless new equally nutritious food can replace fish.

Implementing adaptive actions in response to fishery losses likely required fishers to be willing to adapt behaviors (e.g., changing consumption behavior), or to proactively invest in assets (e.g., in infrastructure to fish longer or further way, acquire new gears) (Green et al., 2021). Yet in the cases fishers were not willing or able to make new gear investments or adapt their behaviors of going longer and further to fish, they may have abandoned fishery activities, or may have even left their communities, as found to be common in the region (Pinto et al., 2022). The social and economic costs of adaptation though have never been qualified or quantified by the developers of the dams underlying underestimation of impacts and burdens carried by the affected people. Although our study has focused on the Madeira dams, our findings provide insights on potential challenges faced by fishers and adaptations communities may need to evolve to maintain livelihood outcomes in other regions where hydropower is rapidly expanding. These regions include different areas across the Amazon as well as in other tropical river basins such as the Congo, the Mekong, and the Yangtze where hundreds of dams are planned to be built. Accounting for these costs and improving adaptation capacity while carefully assessing trade-offs that are inherent in adaptation strategies (Cinner et al., 2018) will be essential to promote fair and transparent mitigation and compensation processes in our study region and elsewhere.

Credit author statement

C.C.A.: Conceptualization, Funding acquisition, Methodology, Investigation, Formal analysis, Writing – original draft, Writing-Reviewing and Editing. J.L: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing- Reviewing and Editing. A.M.: Writing – Reviewing and Editing. E.F.M.: Conceptualization, Funding acquisition, Writing- Reviewing and Editing. J.D.-G.: Conceptualization, Investigation, Writing – Reviewing and Editing. I. R.A.S.: Investigation, Writing – Reviewing and Editing. M.C.L.: Conceptualization, Funding acquisition, Writing – Reviewing and Editing. C.R.C.D.: Conceptualization, Investigation, Writing- Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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