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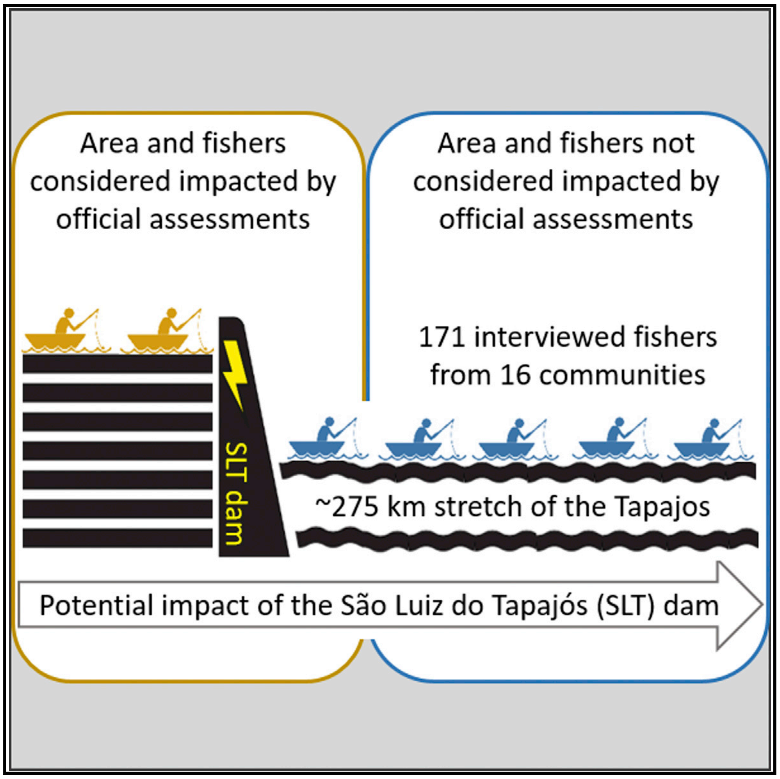
Fishers' Knowledge Indicates Extensive Socioecological Impacts Downstream of Proposed Dams in a Tropical River

Graphical Abstract



Highlights

- We estimated fishers' socioecological vulnerability downstream of a proposed dam
- We created a vulnerability scenario from interviews with 171 fishers in 16 communities
- The majority of the important fish for the fishers would be affected by the planned dam
- The area affected by the dam greatly exceeds that acknowledged by official assessments

Authors

Anne Runde, Gustavo Hallwass,
Renato A.M. Silvano

Correspondence

renato.silvano@ufrgs.br

In Brief

The impacts of hydroelectric dams on small-scale fisheries may have been underestimated. In this study, we estimated fisheries' vulnerability downstream of a proposed dam through interviews with 171 fishers in 16 communities along a ∼275-km stretch of the Tapajos River in the Brazilian Amazon. The results show that most of the exploited fish would be affected by the planned dam, and thus the potential socioecological impacts of planned dams on fisheries and food security would extend far downstream.

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Fishers' Knowledge Indicates Extensive Socioecological Impacts Downstream of Proposed Dams in a Tropical River

Anne Runde,[1] Gustavo Hallwass,[2,3] and Renato A.M. Silvano[1,3,4,*]
[1]Department of Ecology, Universidade Federal do Rio Grande do Sul, Instituto de Biociencias, CP 15007, Porto Alegre, Rio Grande do Sul 91501-970, Brazil
[2]Federal University of Western Pará, Campus Oriximiná, Rodovia PA-254, n° 257, Santíssimo, Oriximiná, Pará Cep. 68270-000, Brazil
[3]Fisheries and Food Institute (FIFO), UNISANTA, Rua Oswaldo Cruz 277, Santos, São Paulo, Brazil
[4]Lead Contact
*Correspondence: renato.silvano@ufrgs.br

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SCIENCE FOR SOCIETY Although dam-building companies usually recognize and compensate for the impacts around and upstream of the dam area, environmental impact assessments (EIAs), which are officially required before dam building, often overlook downstream impacts. We evaluated how far the socioecological impacts of a planned hydroelectric dam on small-scale fisheries would extend beyond the area recognized as affected according to the EIA in the Tapajos River, Brazilian Amazon. We interviewed 171 fishers in 16 communities along a ~275-km stretch of the Tapajos River. A scenario was created, and it showed that the impact of the dam on the fisheries would greatly exceed the area previously defined by the EIA. If the dam was built, it would negatively affect the socioeconomic well-being of the fishers in all studied communities, including those located far downstream of the dam. Therefore, we suggest that a more inclusive assessment of the impacts must be undertaken before dam building is allowed to proceed.

SUMMARY

Brazil's hydroelectricity sector is rapidly expanding, and several dams are planned in Amazonian rivers. The impacts on the fisheries downstream of the dams have largely been overlooked by official impact assessments. Here, we gather fishery baseline data from interviews with 171 fishers in 16 communities along a ~275-km stretch of the Tapajos River, located downstream of a proposed dam. The results indicate that fishing constitutes a key source of food and income for fishers and their communities and that the impact of the dam on the fisheries will potentially extend much further than the officially recognized affected area. By ignoring the effects of the dams on downstream communities, impact assessments have severely underestimated the number of people who would be affected by the dams. Therefore, a thorough evaluation of downstream fishers needs to be conducted prior to river impoundment and be considered by development plans.

INTRODUCTION

Tropical inland fisheries sustain the livelihoods of millions of fishers and their families.[1–3] Despite their importance, these fisheries often remain data deficient and are undervalued or overlooked by policy and management programs.[4–7] This is the case in the Amazon Basin, where a rapidly expanding hydroelectricity sector adversely affects freshwater ecosystems and the subsistence of local fishers.[6,8–10] Limited information, together with inadequate governance and decision making that does not take all parties affected by the dam into consideration, has exacerbated the impacts of the dams.[5,7,11–14] Whereas stakeholders usually recognize the upstream impacts of large storage dams, which are predominantly associated with the flooding of the water-storage area, the impacts on downstream fisheries have largely been ignored or have only been evaluated for the first few kilometers downstream of the dam.[14–16]

Damming of rivers compromises the structure and functioning of the aquatic ecosystems. Among the greatest environmental impacts of dams are alterations to the downstream flow of the river.[9,17] Most lowland dams suppress and disrupt the flood pulse, which creates the seasonal lateral overflow of rivers and lakes and inundates floodplain areas.[9,17–21] These floodplains serve as important sites for the feeding, reproduction, and nurseries of many fish.[18–20,22–24] Most impoundment further decreases the fitness of the species that perform upstream migrations to the headwaters of tributaries for feeding purposes to complete their life cycles or because their spawning grounds are located close to the dam.[17,25,26]

Alterations to the river's downstream flow and its continuity affect species that have evolved specialized biological adaptations to this hydrological signal, particularly with respect to the reproductive and recruitment success of the populations.[19,27–30] The reproduction of some tropical fish is initiated by flooding, and many fish have adapted their gonads to spawn at the beginning of the flood to allow their eggs and larvae to drift into the floodplain areas, increasing offspring survival.[19,28,31–34] Furthermore, the occurrence, duration, and height of flood pulses positively influences fishery yields.[20,32,35–38] Conversely, reduced river flow caused by damming decreases the extent of flooded areas, which leads to a reduction in food availability and adversely affects the species that frequent these areas, in addition to damaging the spawning grounds by making them inaccessible or interrupting the spawning cues.[22,29,30,34,39–41]

The changes to downstream fish diversity, composition, distribution, and abundance after impoundment also cause substantial losses to associated fisheries.[15,24,30,36,40,42,43] In addition to threatening the economic viability of the downstream fisheries, infrastructure projects might also compromise the cultural heritage of these fisheries. For example, several studies have noted a reduction in the use of traditional fishing techniques and fishing sites after construction of Amazonian dams.[5,16]

Brazil is the second-largest producer of hydroelectric power in the world, generating more than two-thirds of its electricity from hydropower.[44,45] Regardless, only approximately half of the country's total estimated hydroelectric potential is currently in operation, and the country faces a massive surge in hydroelectric dam construction to be able to fully exploit this potential.[14,46] The Amazon Basin has the country's highest hydropower potential, and more than 300 large dams are planned in the area.[10,14] The number of planned dams in the Amazon is difficult to estimate, as it varies on a yearly basis according to development plans of the governments involved in political decisions making in the Amazon. Most of these dams greatly exceed 30 MW, and five are mega-dams with an installed capacity of over 1,000 MW.[9] One of these mega-dams is the planned São Luiz do Tapajós (SLT) dam, which, if constructed, will be Brazil's fourth-largest dam.[14]

The SLT dam is planned to be built on the Tapajos River, which is one of the last remaining, clear-water, free-flowing Amazonian rivers.[46] In August 2016, the environmental license of the SLT dam was suspended by the Brazilian Institute of Environment and Renewable Natural Resources due to anticipated impacts of the dam's reservoir on indigenous land. However, the completion of the SLT dam is of political interest, and the suspension is likely to be reversed,[14,47,48] as has already occurred within the licensing processes of other Brazilian dams that were considered politically important.[49]

The lack of sufficient baseline information about the dependence of downstream fishers on aquatic resources, as well as the potential underestimation of impact area, increases the probability of the underestimation of the impacts of the dam.[5,14,16,49,50] In this sense, the environmental impact assessment (EIA) that was conducted to issue the environmental license of the SLT dam was considered weak and biased by specialists.[49] In addition, impacts on the cultural heritage of fisheries as well as spiritual loss have not been investigated in many dam projects, as is the case for the SLT dam, where this impact has been ignored.[49]

There are no baseline studies on small-scale fisheries in the middle reaches of the Tapajos River that would be affected by the SLT dam, although there is information about the fisheries in the lower Tapajos River.[51–54] Local ecological knowledge (LEK) is increasingly used to fill gaps in scientific knowledge and to evaluate environmental changes while enhancing communication and collaboration between researchers and resource users.[54–58] Studies based on LEK have contributed to improving the knowledge about the distribution and abundance of species;[59–63] species extinctions;[64] ecological aspects of species, such as migration, diet, and reproduction;[65–68] and environmental and ecosystem changes.[69–71] In addition, fishers' LEK has been applied to evaluate the socioecological effects of dams on the flow regimes of a tropical river.[72] Amazonian fishers have detailed LEK about fish ecology and fisheries dynamics.[42,54,58,73,74] This LEK of Amazonian fishers has been successfully applied to evaluate the impacts of large hydroelectric dams on fisheries.[16,42]

In the present study, fishers' LEK was used to characterize the small-scale fisheries in 16 communities located along a ~275-km stretch of the Tapajos River. The first objective of the study was to generate baseline fisheries data downstream of the proposed SLT dam by comparing fishing activity (fish catches, fishing gear, and sites) between the middle and lower regions of the Tapajos. The second objective was to use these data from the fisher LEK and literature to evaluate the vulnerability of the fishers to a future impoundment by developing a scenario of the potential effects of the dam on the fish and the fisheries.

We quantified the potential spatial range of the effects downstream of the proposed SLT dam to the mouth of the river. We interviewed 171 fishers from 16 communities located along a ~275-km stretch of the Tapajos River downstream of the planned SLT dam. As such, we were able to evaluate if and how far downstream the impacts of hydroelectric development on fishing would extend beyond the area usually recognized as the affected area based on the EIA. Therefore, the broad spatial scale and the consideration of the communities located far downstream of the proposed dam are novel aspects of this study. The results indicated that the impoundment is expected to negatively affect fisheries much further than considered by the EIA of the planned dam. Potential impacts could reach communities near the mouth of the river, which is located ~275 km downstream of the dam. The dam could decrease the abundance of some of the most-caught fish in the studied communities, therefore putting the livelihoods of fishers and their families at risk. This study will also act as a reference point for future ecological and economic changes, in addition to providing a new methodological approach for evaluating socioecological impacts from dams in poorly studied tropical rivers.

RESULTS

Profile of the Fishers

The interviewee ages ranged from 20 to 86 years with a mean age of 48 years (±13.25 [SD]) and a mean community residence time of 38.6 years (±16.27 [SD]). One in 15 fishers was a woman (n = 11 women, n = 160 men). The fishers had been fishing for an average of 30 years (±14 [SD]). Approximately one-sixth (n = 26) of the interviewed fishers were illiterate, and none had a higher education than secondary school.

The average fishers' household consisted of four people, including the fisher (±1.98 [SD]). Some households (13%) had

Table 1. Economic and Dietary Importance of Fishing in the Lower and Middle Tapajos

	Importance of Fishing (Percentage of Fishers)			
	As an Income Source in Lower Tapajos	As an Income Source in Middle Tapajos	As a Source of Animal Protein in Lower Tapajos	As a Source of Animal Protein in Middle Tapajos
Most important	44.79%	87.96%	92.62%	82.81%
Second most important	46.88%	9.96%	7.38%	11.33%
Third most important	8.33%	2.07%	0.00%	5.86%

Shown are the importance of fishing as an income source and the importance of fish as a source of animal protein in the fishers' diet. The table shows the percentage of fishers who ranked fish among their main animal protein consumed when given choices (cattle and pigs, among others; see Note S2).

7–12 inhabitants, while the rest of the households were occupied by six or fewer people. The sizes of the households did not differ significantly between the middle and lower Tapajos (Fisher's exact test, $p > 0.05$).

Fishing was identified as a very important economic activity by community leaders and the interviewed fishers (Table 1). In addition, most of them considered fish to be their most important source of animal protein (Table 1). The importance of fishing as an income source and for the fishers' diet was irrespective of whether they were from the lower or middle Tapajos. However, in the lower Tapajos, approximately half of the fishers (45%) considered fishing to be their most important economic activity, which was significantly different (Fisher's exact test, $p < 0.001$) from the middle Tapajos, where 88% of the fishers considered fishing to be their most important economic activity (Table 1). In addition to fishing, 67% of the fishers in the lower Tapajos and 18% of the fishers in the middle Tapajos engaged in small-scale agriculture, which was the second most relevant activity. Other income sources were hunting, small-scale animal husbandry or aquaculture, government jobs, non-timber forest products, tourism, and handicrafts. Apart from the fishers, 22% (n = 38) of the fishers' partners also pursued an economic activity that contributed to the household income. Of these, 12 also practiced fishing as an economic activity.

In general, employment significantly differed between the middle and lower Tapajos (Fisher's exact test, $p < 0.01$), as in the lower Tapajos most fishers (87% of respondents) pursued two or more economic activities, while in the middle Tapajos most fishers (57% of respondents) had only one economic activity (Table S1). Fishers 30 years old or younger pursued significantly more economic activities than older fishers (31–60 years old and ≥ 61 years old) in the middle Tapajos ($H = 6.24$, $p = 0.04$). On average, in the middle Tapajos, the younger fishers had 2 (±1.3 [SD]) economic activities, while fishers of 31–60 years had 1.5 (±0.6 [SD]) economic activities and the older fishers (≥ 61 years old) had 1.4 (±0.8 [SD]) economic activities. However, in the lower Tapajos, economic activities did not differ among the fisher age categories ($H = 0.64$, $p = 0.72$), where fishers had on average two economic activities.

On average, the fishers fished four days per week in the lower Tapajos and five days per week in the middle Tapajos. Fishers from the middle Tapajos spent significantly more time fishing per week than those from the lower Tapajos ($U = 1{,}115.5$, $p <$ 0,0001, Figure 1A). Fishers from the middle Tapajos caught significantly more fish (on average double the number) in terms of weight per week than those in the lower Tapajos ($U = 1{,}474.5$, $p < 0.001$, Figure 1B). However, the catch per unit effort (CPUE) did not differ between the lower and middle Tapajos (Figure 1C, $U = 2{,}145.5$, $p = 0.3$), as fishers from the middle Tapajos caught more fish through greater effort.

The fishers from the lower and middle Tapajos differed regarding the commercialization of the fish caught (Fisher's exact test, $p < 0.01$), as more fishers from the middle Tapajos (75%) than from the lower Tapajos (8%) reported selling their fish outside of the community (Figure 2). In addition, many fishers mentioned selling their fish within the community—in numbers, 81% of fishers in the lower Tapajos and 49% of fishers in the middle Tapajos.

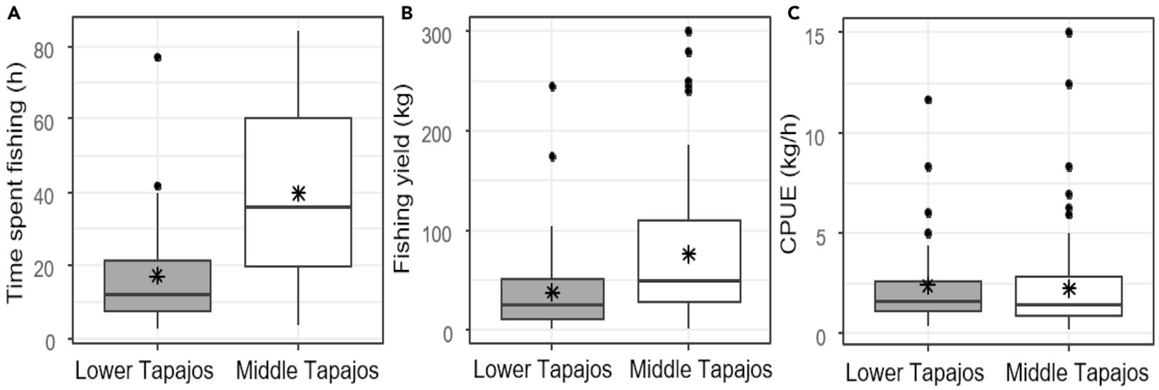

Figure 1. Fishing Effort, Fishing Yields, and Catch per Unit Effort in the Lower and Middle Tapajos

Weekly time spent fishing by the fishers (A), fishers' weekly fishing yields (B), and catch per unit effort (C) in the lower and middle Tapajos. Mean values are represented by the asterisks. Outliers are plotted as individual data points. Vertical bars represent standard deviation, and horizontal bars represent median values.

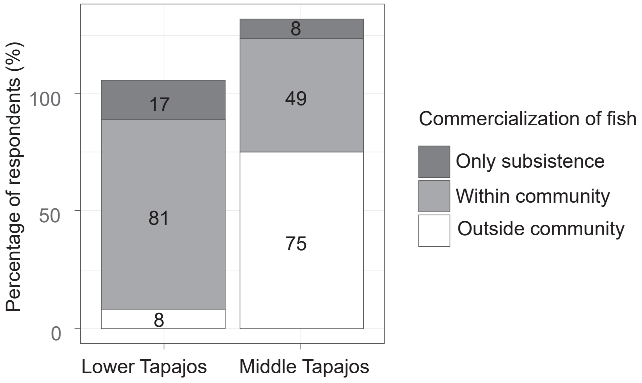

Figure 2. Commercialization of Fish by the Fishers from the Middle and Lower Tapajos

Commercialization within and outside of the community were not mutually exclusive. The sum of the percentage of respondents exceeded 100% because the fishers could cite more than one type of commercialization for the caught fish.

The preferred gear in both the middle and lower Tapajos were gill nets (used by more than 90% of fishers) and hooks and lines (used by more than 60% of fishers), followed by cast nets, longlines, fishing rods, and several spearfishing tools, including harpoons, tridents, spears, and bows and arrows (Figure S1). The choice of fishing gear did not differ among communities or between regions (permutational analysis of variance [PERMANOVA], $p > 0.05$).

The fishing sites used by the fishers differed significantly within seasons in lower (wet: $\chi^2 = 64.1$, $p < 0.0001$; dry: $\chi^2 = 109.8$, $p < 0.0001$) and middle Tapajos (wet: $\chi^2 = 167.2$, $p < 0.0001$; dry: $\chi^2 = 296.1$, $p < 0.0001$). Most of the fishers used the river to fish in both wet and dry seasons, and the lakes were the second most commonly used sites (used by around 30% of the fishers in the wet and dry season). In addition, flooded forests were more frequently used in the lower Tapajos than in the middle Tapajos and even exceeded the use of the lakes in the wet season in the lower Tapajos (Figure S2).

When the fishers were asked for their five most important types of fish, 26 species or groups of species were mentioned by fishers, with 19 in the lower and 25 in the middle Tapajos (Figure 3; Table S2). The five most important fish cited by fishers are, for the purpose of this paper, referred to as "prioritized" fish (see Experimental Procedures). Five species or species groups, including Aracus, Tucunaré, Jaraquis, and Pescadas, accounted for more than 50% of the relative importance of prioritized species across both regions, while Pacus and Acará were also important in the middle and lower Tapajos, respectively (Figure 3). Of the Acará species group, Acaratinga (*Geophagus* spp.) was the most important and was mentioned by 86% of the interviewees. Overall, the prioritized fish cited by the fishers differed among the fishers, and depended on whether they were from the middle or lower Tapajos and which community they were from (PERMANOVA, $p < 0.001$). Acaratinga, Apapá, Charuto, and Tucunaré were more important in the lower Tapajos, whereas the fishers from the middle Tapajos prioritized Aracu, Barbado, Dourada, Jandiá, Matrinxã, Pirapitinga, Pirarara, and Surubim (Figure 4).

Susceptibility Scenario

Within every community, at least one prioritized fish could be adversely affected by the SLT dam (Figure 5). The scenario considered the frequency with which a prioritized fish was cited by the fishers during the interviews and that each citation of a fish accounted as one. Overall, approximately one-third of the total number of prioritized fish cited by the fishers would be affected because of their dependency on the floodplain and/or because they spawn either at the beginning of or during the flooding (Figure 5). In the integrated scenario, fishers from the communities Nova Canãa and Boa Vista do Tapajós, Barreiras, and São Luiz do Tapajós, which are closest to the proposed dam, would experience the strongest adverse effects. In this category, on average, more than half of the total number of prioritized fish would be negatively affected. This means that the fishers potentially experience negative effects on around half of their fishery catches and

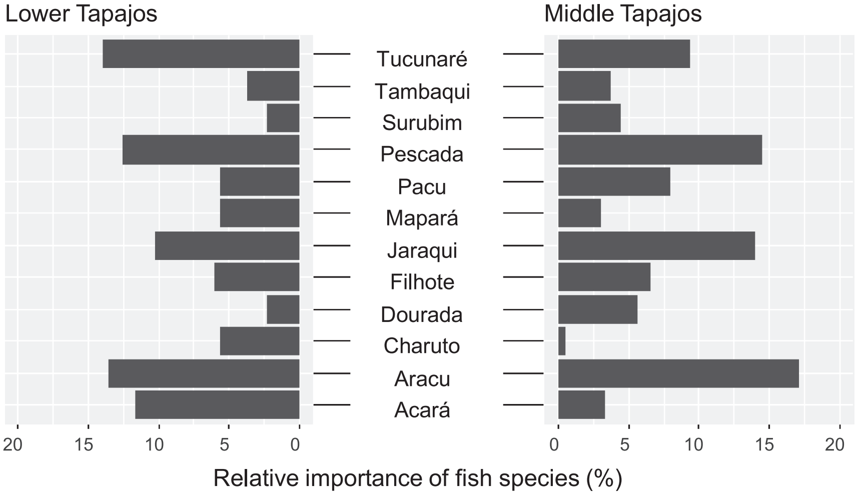

Figure 3. Relative Importance of the Prioritized Fish in the Lower and Middle Tapajos

Each fisher could cite up to five prioritized fish species, and each citation was considered an individual data entry. The species' relative importance is expressed as the percentage of the total fish citations (lower Tapajos, n = 214 citations; middle Tapajos, n = 565 citations). Only the fish species that represented an average of 2.5% of the relative importance considering citations from both regions are shown (for example, if the relative importance of a species is 2% in lower Tapajos and 3% in middle Tapajos, this fish is shown). The scientific names of fish are listed in Table S2.

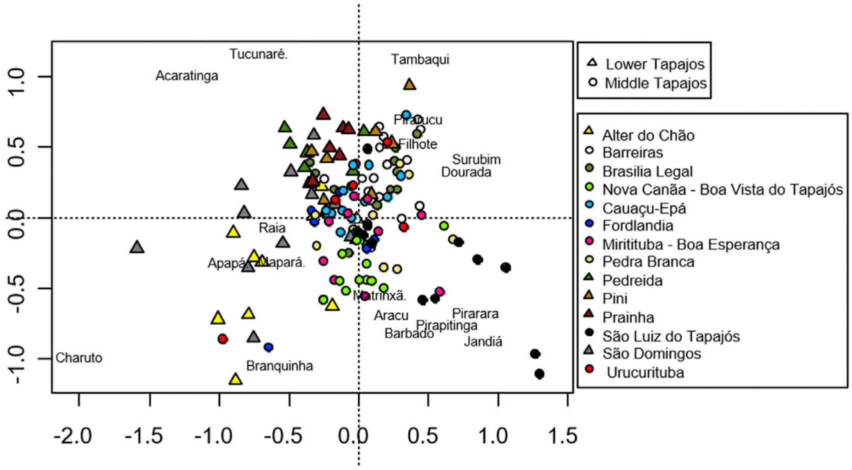

Figure 4. Fishers Grouped according to Their Prioritized Fish

Redundancy analysis with axes 1 (11% of explained variance) and 2 (8% of explained variance) grouping the interviewed fishers according to their prioritized fish from the middle and lower Tapajos. Each dot represents a fisher (n = 171), the colors refer to communities, and the symbols indicate the region of the river (middle or lower Tapajos). The analysis shows the prioritized fish that most contributed to the dissimilarity of cited fish from both regions, middle and lower Tapajos. The scientific names of fish are listed in Table S2.

shows that the effects of the dam could spread far downstream (Figure 5).

DISCUSSION

We evaluated how far the impacts of the planned SLT hydroelectric dam on fishing may extend beyond the area recognized as affected by the official assessment (EIA) in the Tapajos River. The vulnerability of the fishers to the planned dam was shown by analyzing their socioeconomic profile, their fishing activity, and the potential effects of the dam on the fish they consider most important. In addition to acting as a reference point for future ecological and economic changes, characterizing the fisheries downstream of the SLT dam helped to appropriately define the area and people that are likely to be affected by the planned dam. This will improve the understanding of the challenges that the studied communities, as well as other communities located downstream of dams, will face upon dam development. The results of this study could further help to create appropriate mitigation measures and to reconsider downstream impacts from dams besides helping to incorporate LEK in the evaluation of dam impacts not only in the Brazilian Amazon but also in floodplain rivers elsewhere.

On the basis of the socioeconomic profiles of the fishers and their prioritized fish, we found that fishers from all 16 studied communities could be affected if the SLT dam was built and alterations to the downstream flow occurred far downstream. Therefore, the area directly affected by the SLT dam would greatly exceed the area previously defined by the EIA.[75] Other studies have also indicated far-reaching post-damming impacts on fisheries up to approximately 200 km downstream in Amazonian rivers.[15,30,40,42,76] Therefore, the true downstream impacts of the SLT dam may have been underestimated, which could endanger the livelihoods of the fishers who are economically and culturally dependent on the river fisheries.

Fishing Dynamics

The results from the interviews showed differences in the fisheries between the lower and middle Tapajos, primarily in regard to the time invested in fishing, the commercialization and

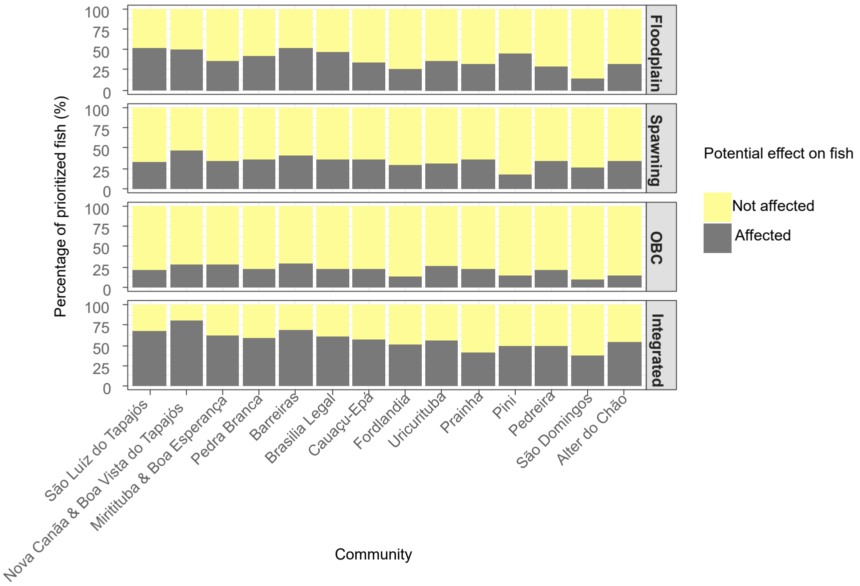

Figure 5. Estimated Potential Effects of Damming on Fishing on the Basis of the Prioritized Fish Cited in the Studied Communities

Estimated potential effects of damming on fishing in the studied communities according to the proportion of prioritized fish and their susceptibilities to impoundment. São Luiz do Tapajós is the closest community to the dam, and the distance from the dam increases from left to right. The affected categories (floodplain, spawning, and other) are those defined in Table S2. The affected percentage of the "integrated" scenario combines the percentage of the species affected within the other categories and gives the total percentage of the species that would be affected upon dam creation.

prioritization of fish, and the fishing sites, indicating the heterogeneous nature of fisheries along this river, which are similar to those observed in other regions of the Amazon.[77–79] The commercialization of fish outside of the community was less important in the lower Tapajos than in the middle Tapajos, possibly because of restrictions on commercialization of fish outside of the FLONA (the protected area of the Tapajos National Forest).[52,54] Many of the interviewed fishers in the lower Tapajos divided their time among two or more sources of employment, whereas fishers in the middle Tapajos, especially older fishers who were more than 31 years old, regarded fishing as their primary employment. The net fishing yields were higher in this region. These results indicated that fishers and communities from the middle Tapajos would be more dependent on fisheries for income, including the fisheries directed at migratory fish species that supply local and regional markets. In addition, the low level of formal education makes older fishers more vulnerable and susceptible to environmental change in the middle Tapajos.[80,81] Nevertheless, in the lower Tapajos fishing still provides income to fishers,[52] and fish can be a source of animal protein that helps to prevent malnutrition.[6,82] Therefore, the differences in the potential vulnerability of these communities need to be considered in the environmental assessments and compensation measures related to development projects, such as large dams, to respond to the needs of the different communities.

The observed differences in the fishing sites among the two studied regions could explain the differences in the prioritized species. The river is narrower in the middle Tapajos, which could make it easier for fishers from the middle Tapajos to catch fish from the main river channel, hence explaining their preference for fish species that migrate along the main river channel, such as the Dourada, Surubims, Barbado, and Matrinxã. In the lower Tapajos, some of the prioritized fish, such as the Tucunarés and Acaratinga, are commonly found in flooded forests and lakes. These floodplain habitats are used by fish and hence by fishers when connected to the main river by the flood pulse,[83,84] so projected changes to the water level upon damming could decrease the use of these fishing sites by fishers, as observed after the construction of the Belo Monte dam.[16] If fishers need to travel more to find new fishing sites, this would increase the total time spent fishing and the fuel costs, thus reducing the economic revenues of the already impoverished fishers. Therefore, even considering the observed differences in the fisheries, both studied regions could be negatively affected by the SLT dam, which could reduce the abundance of the migratory fish in the middle Tapajos and decrease the availability of fishing sites in the lower Tapajos.

Although used less frequently than nets, spearfishing techniques, such as tridents, harpoons, bows and arrows, and spears, were also used by the interviewed fishers in the Tapajos River. Such spearfishing techniques are more complex to use, require experienced users, and have been used by Amazonian fishers for generations as a legacy of the indigenous people.[85] Because spearfishing techniques are commonly used in flooded areas, changes in the flood pulse downstream of the SLT dam could impede the use of these fishing sites. Indeed, the use of a particular spearfishing technique has been disrupted, and knowledge about it is likely to be lost in future generations after the implementation of the Santo Antônio dam in the Madeira River.[5] Therefore, changes in fishing techniques and sites upon river damming can threaten the cultural heritage of fishers downstream.[85]

Twenty-six fish species and groups of species were mentioned by the fishers when asked for their prioritized species; five of these types of fish accounted for more than 50% of the relative importance of the fish citations. Most of these fish, such as Tucunaré, Jaraqui, Mapara, Pacu, Pescada, and Tambaqui, are also the types most frequently caught and sold by small-scale fisheries in other Amazonian regions.[79] The number of fish species prioritized by the interviewed fishers was thus only a fraction of the high fish diversity found in the Tapajos River, which may contain more than 300 fish species.[53,79,86] A reduced number of prioritized species or fish with high economic value has also been observed in other Amazonian rivers, leading to a concentration of fishing efforts directed at preferred fish.[8,79,84] An eventual decrease in abundance as a result of fishing pressure can make these highly exploited fish more susceptible to dam-related impacts, such as increased susceptibilities to recruitment failure, extinction risk, and reduced gene pool size.[8,87,88] Although they prioritize a small number of species, Amazonian small-scale fisheries are heterogeneous regarding their fishery catches.[77–79] This may allow the fishers to exploit other, more resilient fish to compensate for the species that would decrease in abundance upon damming.[89] Nevertheless, because less preferred fish usually have a lower economic value, such a change in fishing after damming can result in economic losses for the fishers over time.[90]

Socioecological Susceptibility of Fishers to Dams

Although the interviewed fishers had several economic activities, fishing was their most important economic activity in the lower and middle Tapajos River, which has also been observed in other Amazonian rivers.[42,77,91,92] Furthermore, the fisher, who was usually a man, was the only person who contributed to the household income in many of the studied families in the Tapajos River. These results were consistent with the observed pattern in other Amazonian regions where women predominantly conduct household activities and do not pursue economic activities.[16,93] The expected losses in the fishery catches from damming would therefore negatively affect the most important, and sometimes sole, income and protein source of the fishers. Because many of the studied households had more than four people, many people rely on this income and would be affected. Reduced fishery catches have compromised the economic viability of fisheries after the implementation of dams in the Amazon Basin, such as the Belo Monte dam on the Xingu River,[16] the Tucuruí dam on Tocantins River,[42] the Santo Antônio dam in the Madeira River,[30] and in other river basins such as the Itaipu dam on the Paraná River in southern Brazil.[90] A particular concern is the likely reduction in well-being of the female fishers. Studies have shown that fisherwomen suffer disproportionately from damming and even become completely economically dependent on men.[16] Consequently, the female fishers would need to receive specific consideration in regard to the compensation and mitigation measures if the dam was built.

As observed in other Brazilian rivers,[90,94] fishers may switch to other fish species or increase their fishing effort (e.g., time spent fishing) to compensate for the changes in the fishing resources caused by the dam. However, in the long term, it is possible that many of the fishers in the studied communities would need alternative sources of income if the fishing yield decreased as a result of the damming. The results showed that the fishers in the Tapajos have a comparably high illiteracy rate and that a low proportion of them have higher education than the Brazilian standard.[95,96] Low levels of education, which are common in rural Amazonian communities,[42,97] may decrease the fishers' chances of taking up alternative employment[98] to compensate for the economic losses from damming. Alternative and new employment opportunities could further be hampered by a lack of community infrastructure, including the difficulty of reaching some communities. Indeed, fishers from downstream of the Belo Monte dam in the Xingu River did not recognize alternative economic activities to compensate for their decrease in fishing profits after dam implementation.[16] Fishers could also shift to other customary economic activities, such as hunting, agriculture, and livestock production,[99] which could generate further environmental impacts. For example, some of the interviewed fishers in the lower Tapajos lived within a conservation unit, and an increase in hunting could intensify the pressure on wild species. Increased pressure on forest resources has, for example, been observed after the installation of the Son La hydropower plant in Vietnam.[100] In addition, land conversion due to increased involvement in animal husbandry and small-scale agriculture may enhance soil erosion and lead to deforestation.[6,30,53,101–104]

The studied fishers in the Tapajos River considered fish to be their most important source of animal protein, as observed in other regions of the Amazon, where the per-capita fish consumption is among the world's highest.[6,105,106] Our results indicated that most of the interviewed fishers mentioned that they sold their fish within the community, and in the middle Tapajos, most fishers also sold their fish outside the community. Given such an importance of fish supply through the studied fishers, the potential decline in fishery yields upon dam construction could threaten food security at both the household (food provision) and regional (fish market) scales throughout the year.[6,16,30,40] Previous studies have shown that after the construction of dams in major Amazonian rivers, downstream fisheries are unable to satisfy the demand of resident populations for fish,[30] and fishing declines could increase the price of fish while creating a dependence on external sources of animal protein.[6,16] Among the studied communities on the Tapajos, this problem may be exacerbated because of the poor infrastructure and lack of access, which could make it difficult and costly to obtain food from external sources. External food sources for local communities are usually more expensive, can be nutritionally poor, and are unreliable due to failures in the market chain.[6,16,97,104,107] Therefore, greater reliance on external food sources may make these communities more vulnerable.[89]

The results of the proposed scenario show that fishers from all studied communities strongly rely on fish that could be affected by the construction of the SLT dam. When considering all categories of the scenario, more than half of the prioritized fish could be affected across most of the studied communities from both the middle and lower Tapajos River. Although we did not ask fishers directly about the dam impacts, when they were asked whether they think that fishing will be better or worse in the future, 18 fishers mentioned the planned dam as a reason for why they think that fishing will be worse for them in the future, as the dam would reduce fish supply. All of these fishers were from the middle Tapajos, which corresponds to 15% of the fishers interviewed in that region. Similar negative post-impoundment effects have been observed on the fitness and abundance of several fish important to fishers in the Tocantins River in the area downstream of the Tucuruí dam.[40,42] For many of the communities more than 100 km downstream, more than 50% of the prioritized fish could potentially be affected by the dam and its alterations to the downstream flow. This is twice the size of the directly affected area according to the previous EIA. Such potential impacts of the dams on large proportions of the fish are expected to affect the fishers' catches, as has already been observed for fisheries downstream of dams in Amazonian rivers.[42] In the Tocantins River, for example, the CPUE decreased by 65% in the 2 years following dam development,[36] while a long-term study in the same region showed a 19% decrease in the contribution of downstream fisheries to the total fishery production.[43] Additionally, downstream fisheries suffered losses of 34% in their mean monthly catches after construction of a dam in the Madeira River.[30] Recent studies have highlighted the influence of maintaining a natural flood pulse on the fishing yields in the Amazon River.[38,108]

Although the impacts of the SLT dam would affect all studied communities along the Tapajos River, those communities closest to the dam would be more strongly affected. Previous studies report drastic decreases in water levels, including occasional drying out of the areas immediately below a dam.[76,109,110] Low water levels throughout most of the year can separate marginal lakes from the main river, thus trapping fish in these isolated aquatic habitats.[31,76,109] Such a lack of habitat connectivity, in addition to the accumulation of deoxygenated water enriched with toxic gases, can lead to mass mortality of the fish immediately downstream of dams or in isolated marginal pools.[76,111,112] On the other hand, high concentrations of fish have often been observed immediately below the dam, resulting in productive tailrace fisheries, which benefit from the high abundances of migratory species, including the highly valued commercial fish that were prioritized by the studied fishers, such as the Surubims and the Dourada.[23,113–117] Although initially highly productive, tailrace fisheries are usually unsustainable because they are soon overexploited, leading to a decrease in fish abundance.[11,76] Therefore, monitoring, compensation, and mitigation measures should be directed to those downstream communities that are closer to the dam, including measures aimed at controlling and managing eventual tailrace fisheries.

Study Limitations

Although useful, LEK-based information should be carefully interpreted.[42,118] In this regard, the interview question about the most important fish could be biased toward economically high-value species, as has been observed in previous studies.[42,119] Therefore, the reported results should be effective to indicate the potential dam impacts on fisheries and fishers but not as a measure of the dam impact on the whole fish assemblage, as some less valued fish species might be mentioned less frequently by the fishers. This should be acknowledged when assessing the ecological impacts of dams and developing adequate mitigation measures.

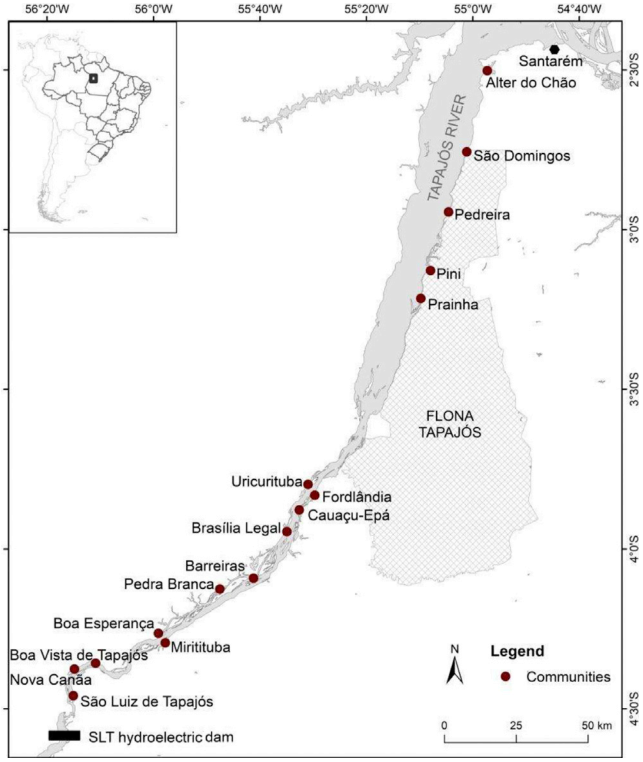

Figure 6. Map Showing the Study Region in the Tapajos River, Brazilian Amazon

The lower and middle downstream regions of the planned São Luiz do Tapajós (SLT) hydroelectric dam. Red dots indicate the communities where interviews were conducted. The black rectangle indicates the planned SLT dam site. FLONA refers to the protected area of the Tapajos National Forest. The inset shows the location of the studied region in Brazil.

The scenario developed in this study might underestimate the impacts of the dam because of the lack of biological knowledge about Amazonian fish.[6] Although fish species belonging to the Characiformes or Engraulidae have been considered susceptible to damming because they reproduce at the beginning of or during flooding,[28,120,121] not all species from these taxa that were found in the studied region show the same spawning behavior. The developed scenario could also underestimate the impact of the dam because it does not consider migratory fish that could have their long longitudinal migrations along the Tapajos interrupted by dam construction. These migratory species were well represented among the prioritized fish, including large catfish with high commercial value,[53,122] some of which may enter Amazon tributaries during the spawning migrations,[25,123] including the Tapajos River.[74] Therefore, the studied fishers, especially those of the middle Tapajos, could experience economic losses due to reduced availability of migratory fish after impoundment, as reported in other rivers.[42,90] Migratory species were not included as a susceptibility category in the scenario because there was a possibility that recruits of the migratory species coming from the lower Amazon River could compensate for the decrease in the migratory species downstream of the dam.[36] However, migratory species are expected to decline everywhere in the Amazon given that a growing number of dams are blocking the route to their spawning grounds and intercept the movement of their eggs and larvae.[9,10,25,116]

On the other hand, the proposed scenario did not consider potential mitigation measures, such as fish passages or run-of-the-river plants, which would decrease the water-storage area compared with dams with reservoirs.[15,75] However, fish passages have proved to be inefficient or even harmful in the context of tropical hydropower development,[116,124] and Amazonian run-of-the river dams have been shown to affect river flow, floodplain habitats, and fish spawning.[16,30]

Finally, this study did not consider the possibility that water inflow from tributaries of the Tapajos River could compensate for the water shortages caused by the dam in the lower Tapajos region. However, only one smaller river (<100 m wide) flows into the Tapajos River downstream of the proposed SLT dam, which suggested limited buffering capacity for water shortages at least as far as the area where the Tapajos narrows (Figure 6). Moreover, another 43 dams are planned to be built in the Tapajos Basin, not all of which are run of the river, which should cumulatively withhold and change the flow of the water, thus greatly exacerbating the downstream impacts.[47,48] Furthermore, climate change, which has already been identified to influence the flood pulse and decrease precipitation in the Amazon, is suggested to worsen the adverse impacts of changes to the flood pulse and a dryer environment on the floodplain fish.[10,102,125]

Recommendations for Future Assessments and Research

The results of this study indicate the need to consider the benefits and costs of the dam impacts on tropical rivers, such as the Tapajos, in relation to the environment and the people affected. The interviews with fishers indicated at least three main dimensions of potential effects of the SLT dam on the people living along the Tapajos River: (1) economic factors, such as the reduced commercialization of fish and reduced household income; (2) social factors, such as changes or decreases in the availability of protein and need to change employment; and (3) cultural factors, such as changes in identity and stress to fishers and their families. Therefore, decision makers, funding agencies, and impact assessments should consider all these socioeconomic effects as well as the quantity of people and the size of the affected area.

Impact assessments should include a more realistic estimation of the affected downstream areas and extend the directly affected area much farther downstream of the SLT dam than according to the previous EIA.[75] Therefore, preventing the construction of the SLT dam because of its socioecological impacts on the communities located downstream should be considered. If the developers decide to build the proposed dams in the Tapajos River Basin, mitigation measures must consider the cumulative impacts of these dams far downstream. Because of the fisheries' heterogeneity along the lower and middle Tapajos, one-size-fits-all mitigation measures are likely to fail. Instead, plans to alleviate the adverse effects of damming must be developed that consider each community as a management unit and tailor the efforts to the needs of the fishers.

Research is needed regarding the biology and, in particular, the habitat use, migration, and reproduction of the fish species in the Tapajos and other Amazonian rivers, which would help to determine their susceptibilities to dam development, thus making the developed scenario more accurate. Further research could also incorporate indicators related to the fish life history strategies to estimate the potential impacts from the dam development.[126] More research is also required on the connectivity of the floodplains to improve the development of measures to remediate the predicted adverse impacts of the dam on the flood pulse.[23,27,32,127] Systematic monitoring of downstream fisheries, such as the collection of data on landings, fishing efforts, market prices, and market chains, especially where and to whom fish are sold and the costs associated with fishing, should be applied to reinforce the baseline data and to make communities and decision makers more prepared for possible future environmental and economic changes. Future research could also investigate fishers' own perceptions of the potential risks associated with the dam, for example, with respect to their sources of income and food.

Conclusion

Although hydroelectric dams such as the planned SLT dam generate necessary energy, the costs of these dams to society and the downstream fisheries cannot be ignored. Similar to many planned dams in tropical rivers, the SLT dam is expected to adversely affect households as well as local and regional economies hundreds of kilometers downstream. The data gathered through this study may serve as a baseline against which the impacts of the SLT dam, or other regional anthropogenic impacts, could be assessed in the future. Without careful consideration, declines in small-scale fisheries and the resultant pressure on associated fishers, their families, and both the local and regional economies are certain to accompany the development of the SLT dam and other dams in tropical rivers. The data may also be used to quantify the true costs of the SLT dam in the Tapajos River and to Brazilian society. Ignoring the costs and effects of the dam on the downstream communities would greatly understate its real impacts, which could severely affect people whose livelihoods depend on riverine resources. The approach adopted in this study of developing a scenario based on fishers' LEK and available biological information can be a simple and efficient method for assessing the impact of dams on small-scale fisheries. This method can thus serve as a model to be widely applied globally in other poorly known tropical rivers that are subjected to hydroelectric development.

EXPERIMENTAL PROCEDURES

Study Area

The Tapajos Basin drains an area of 493,000 km^2 between the latitudes of 2° and 15° south and 53° and 61° west in the Brazilian states of Pará, Mato Grosso, and Amazonas. The Tapajos River expands over 851 km and is one of the most important tributaries in the southern margin of the Amazon.[128] It has floodplain areas with marginal lagoons, flooded forests, lakes, and river channels that are enclosed by forests that principally connect with the main river during periods of high water.[74] It is subject to an annual flood pulse whereby water levels increase from December or January until May or June and then decrease.[129] The human population in the Tapajos Basin corresponds to nearly half a million people, of which approximately 26,000 are located in communities in two protected areas in the lower Tapajos, some of which were included in this study.[130]

This study was conducted along a ~275-km stretch of the river downstream of the proposed SLT dam (4° 33′ 7,51″ S, 56° 16′ 42,76″ W) in the state of Pará, Brazil (Figure 6). The study area was divided into two regions on the basis of the river's heterogeneity, and these were mostly related to differences in width, which influence the fish assemblages and fisheries.[51–53] The region from the community of São Luiz do Tapajós to the city of Aveiro (approximately 125 km long) has a maximum river width of approximately 5 km and is referred to in this paper as the middle Tapajos. The region from Aveiro to Santarém (approximately 150 km long) has a river width of approximately 10–15 km and is referred to in this paper as the lower Tapajos (Figure 6). The river width does not include floodplain areas. The area that was considered to be affected socioeconomically by the EIA exceeds the area of biological impact.[75] To be conservative, we based our impact study on the larger socioeconomic impact area, which is approximately 50 km downstream of the dam according to the EIA.[75] The directly affected area was defined by the EIA as the area where the scope of the impacts falls directly on the environmental resources, modifying their quality or altering their potential for conservation or use during all phases of the project. The proposed dam will exceed 7 km in width and have a maximum capacity of 8,040 MW and a reservoir area of 729 km^2 that will stretch along 123 km of the Tapajos River and 76 km of the Jamanxim River, which is a tributary of the Tapajos River. The depth near the proposed dam will be approximately 50 m.[131] No fish passages were mentioned in the project proposal.

Data Collection

One hundred seventy-one fishers from 16 communities were interviewed between March and May 2018. The communities had a minimum distance of approximately 10 km between each other, and ten or more fishers from the communities consented to participate in the study. The communities Miritituba and Boa Esperança, as well as the communities Nova Canãa and Boa Vista do Tapajós, were combined into single study sites because these pairs of communities were separated by fewer than 10 km (Figure 6), so the fishers' fishing grounds overlap and possibly exploit the same fish stocks. Four of the studied communities were situated inside the FLONA (Figure 6).

Upon arrival in the communities, the research was explained to the community leaders and oral permission to conduct the research was acquired. Next, an interview addressed to the leader inquired after general information about the community (Note S1), after which the leaders nominated fishers known to them to be interviewed. After explaining the research and receiving their oral consent to participate in the study, these fishers were interviewed and were then asked to suggest other fishers for interview. The interviews usually lasted approximately 45 min. The procedure continued until no further new names were mentioned, indicating that all fishers who were available in the community had been interviewed. This so-called snowball method has successfully been applied in similar studies.[42,54,66] The interview conducted with the fishers (Note S2) was semi-structured and consisted of four parts: (1) the socioeconomic profile, which included age, education, financial situation, and governmental support; (2) discussion of resources and economic activities, including diet; (3) discussion of fishing, including fishing equipment and sites, fishing yields, time spent fishing, and commercialization of fish; and (4) discussion of catch composition. Since the interview was part of a larger project, not all questions were used for the purposes of this study. It was explained to the interviewees that they could skip questions if they did not feel like answering them. Fish species were identified by their local common names, some of which encompassed groups of species (Table S2).

Data Analysis

Data Preparation

The fishers' reported weekly time spent fishing was calculated by multiplying their time spent fishing per day by the number of days spent fishing per week and then averaging the values of all the fishers. A fisher's weekly fishery yield was calculated by multiplying the normal daily weight (kg) of fish caught by the number of days spent fishing and dividing this by the number of fishers participating in the fishing trip. Because fishing yields can vary daily, fishers were asked to state the amount of fish that they most often catch. The average yield of all fishers was then calculated. Fishing trips lasting consecutive days were considered as 12 h of fishing time for the analyses, as the fishers did not spend the entire time fishing. However, overnight fishing trips were not incorporated into the analysis of the weekly fishing yield because it was unclear whether these overnight trips were considered by fishers when answering the number of days they fished per week. In any event this exclusion had a low impact on the estimation of fishing yields, as only 7.2% of the fishers cited overnight trips. Eleven of these trips were from the middle Tapajos (9% of 118 fishers that responded to this question) and one was from the lower Tapajos (2% of 48 fishers). The CPUE was calculated by dividing the fishing yield by the fishing time cited by the interviewed fishers. The answers about where the fishers sold their fish included "outside of the community (fishmonger, middleman)" and "in the city or within the community." These two responses were combined into "outside of the community" for the analysis since, for the purpose of this study, a more precise separation was not required. For the interviews, the questions about the fishers' economic activities and diets were divided into the dry and wet seasons. After verifying that there was no significant difference between the values in the wet and dry seasons, their averages were considered the average economic activities and diets throughout the year.

The number of economic activities cited was compared among three age categories of the interviewed fishers, which were ≤30 years old, 31–60 years old, and ≥61 years old in the lower and middle Tapajos. These age categories were broken down at regular intervals to include younger (≤30 years) and older (≥61 years) fishers, considering the minimum retirement age of women in Brazil in 2018, where women 61 years or older would theoretically be retired.

Scenario Development

In accordance with the literature, fish species were considered to be affected by hydroelectric development according to three categories: (1) use of the floodplain, (2) spawning at the beginning of or during flooding, and/or (3) possession of other biological characteristics that make them susceptible to impoundment, such as certain types of migratory behavior (Table S2). Lastly, the categories were combined into an integrated scenario to visualize the possible future effects of the dam on the five most important species of fish mentioned by fishers during the interviews. In the case of dissimilarity of the biological characteristics among fish species grouped under a common name, they were considered separately within the analyses. The responses of individual fishers about their five most important species, referred to as "prioritized" fish, were grouped by community for the analyses because the mitigation measures upon dam construction are applied at the community scale.

Statistical Analysis

To compare the relative importance of the fish between the lower and middle Tapajos, fish were ranked according to the number of fishers that mentioned them among their five most important species. PERMANOVAs using the Bray-Curtis distance and randomization (1,000 permutations)[132] were used to verify the significance of the dissimilarities among the prioritized fish (dependent variable in the matrix) according to region (middle or lower Tapajos) and the community (independent variables) and considering the interviewed fishers as the units of analysis (replicates) in the matrix. The same analysis was conducted considering the fishing equipment as the dependent variables in the data matrix. The analyses were based on the categorical data (presence or absence) according to the occurrence of citations for fish species and fishing equipment. The dissimilarity of the prioritized species from the different communities and regions was visualized through a multivariate redundancy analysis based on a data matrix relating fish mentions with interviewed fishers and considering communities and regions (middle or low) as factors. Since Acaratinga (*Geophagus proximus*) was considered separate from the remaining species of its genera by the majority of fishers, it was considered separate from the Acará in this analysis.

Differences among the time spent fishing (h) and fishing yield (kg) between the middle and lower Tapajos were analyzed by the Mann-Whitney U test. The number of economic activities among the fisher age categories was tested by Kruskal-Wallis (H) analyses with the a posteriori Dunn test for the lower and middle Tapajos. For the cross-regional comparison of the categorical data, such as fisher employment, diet, and commercialization of fish, Fisher's exact test of independence was used to compare the frequency distribution of the number of fishers (dependent variable) who reported the independent variables between the lower and middle Tapajos. This test was also used to check for significant differences in the socioeconomic characteristics between the low and high water levels. The number of fishing sites cited within each season in the lower and middle Tapajos were tested by chi-square test.

The statistical analyses and graphical representations were completed in RStudio[133] and ggplot2.[134] Outliers were fully incorporated into the analyses and displayed in the graphics. Normality of data was examined with the Shapiro-Wilks test, and homogeneity of variances was assessed with the Bartlett test. Data that did not fulfill the requirements for parametric tests were log-transformed to achieve a normal distribution and homoscedasticity, or non-parametric tests were used.

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.oneear.2020.02.012.

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AUTHOR CONTRIBUTIONS

Conceptualization, A.R. and R.A.M.S.; Methodology, A.R., R.A.M.S., and G.H.; Formal Analysis, A.R. and G.H.; Investigation, A.R., R.A.M.S., and G.H.; Data Curation, A.R.; Writing – Original Draft, A.R.; Writing – Review & Editing, A.R., R.A.M.S., and G.H; Visualization, A.R.; Supervision, R.A.M.S.; Project Administration, R.A.M.S.; Funding Acquisition, A.R. and R.A.M.S.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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