Clean energy and poor people: ecological impacts of hydroelectric dams on fish and fishermen in the Amazon rainforest *

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Abstract: - Hydroelectric power generated from man-made reservoirs is sometimes regarded as a ‘clean’ or environmental friendly energetic source, due to the lack of pollution mainly from liquid and solid effluents. However, several researchers have been claiming that such form of energy production may sometimes generate intense and irreversible environmental impacts, especially when large reservoirs are built in natural tropical regions, which usually have a rich biodiversity of aquatic and terrestrial organisms. Our major goal is to provide a brief review of one dimension of such reservoirs’ impacts in a large tropical region: the ecological effects of large dams and reservoirs to fish and fisheries in the Brazilian Amazon rainforest. We also analyzed in detail the ecological effect of Tucuruí reservoir on fish and fisheries of the Lower Tocantins River, as a study case. Amazon people rely mostly and sometimes solely on fisheries as their main source of animal protein and cash income. Some of the large reservoirs may had potentially affected this economic activity mainly in the region downstream from the dam, due to changes in the flooding regime, retention of nutrients in the reservoir and blockage of reproductive migrations of economically important fishes. Such effects may generate or enhance poverty in short time, social conflicts and economic isolation of riverside fishing communities, but these problems are less understood than direct changes on fish communities. In a recent survey (2006-2008) in the Lower Tocantins River, interviewed fishers from eight communities mentioned impacts of the Tucuruí reservoir, such as decrease in the abundance of fish. Nevertheless, these fishers still maintain a frequent fishing activity, which indicates that at least some commercial fishes have been able to cope with the reservoir effects, some may have even benefited from this, although the composition of fish catches changed compared to pre-impoundment period (before 1985). A possible factor allowing the persistence of fishes and fisheries in this region may be the floodplain with several lakes, which are important fish spawning sites, according to fishers and biological data. This survey also highlights that effects of a large dam may extend far beyond the reservoir itself, and that fishers have a good deal of knowledge about their aquatic environments and changes to it. Also, the potential effects of alleged ‘less impacting’ energy production on people and fish should be better acknowledged in political and economic decisions regarding energy issues.

Key-Words: - Reservoirs, Energy production, Ecological economics, Human ecology, Brazilian Amazon, Fish ecology, Tropical fish, Environmental impact, Development, Tropical rivers

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1 Introduction

Brazil, as many other tropical developing countries, has a growing demand for electric energy power, in order to fulfill the increasing needs of the urban populations and industrial economic activities. Hydroelectric power generated from man-made reservoirs has been the major energetic source in Brazil, due to the extensive Brazilian's river drainage systems, especially at the Amazon Basin [1,2]. Such hydroelectric power has been sometimes regarded as a 'clean' or more environmental friendly energetic source, due to an alleged lack or reduced pollution from liquid and solid effluents. However, hydroelectric production may generate intense and irreversible environmental and social impacts, especially when large reservoirs are built in natural tropical regions [1,3,4,5,6].

Our major goal is to provide a brief review of one dimension of reservoirs' impacts in a large tropical region: the ecological effects of large dams and reservoirs to fish and fisheries in the Brazilian Amazon rainforest. We also analyzed in detail the ecological effect of Tucuruí reservoir on fish and fisheries of the Lower Tocantins River, as a study case. We thus summarized current information regarding large tropical reservoirs using Brazilian Amazon as a background, in order to highlight the need of a more careful consideration of potential socio-environmental impacts related to hydroelectric power in Brazil and elsewhere.

2 Large tropical Reservoirs and fisheries

2.1 Large reservoirs in tropical rivers

Large reservoirs and dams have some well recognized synergistic environmental impacts on tropical river systems, such as changes in water quality (eutrophization and reduced oxygen levels) due to decomposition of submerged vegetation; changes in the natural flooding regime of river stretches upstream and downstream from the dam due to reservoir operation; proliferation of disease borne mosquitoes; retention of sediments and nutrients in the reservoir, affecting floodplain's island formations and fish feeding downstream from the dam; changes in the overall fish species composition and fish community structure (throphic levels, food chain) and drastic reduction in the abundance of populations of large migratory fishes, due to the interruption of their reproductive migrations [1,3,4,5,7,8,9,10,11,12,13]. Furthermore, the reservoirs may generate high emissions of greenhouse gases, such as methane and carbon, therefore not being necessarily 'clean', nor less polluting than fossil fuel alternatives [14,15,16]. Besides these ecological impacts, large tropical reservoirs have been also generating social impacts, such as reduction in fisheries productivity due to the ecological changes mentioned above; relocation of people due to reservoirs' flooding on their homelands, potentially causing social and cultural conflicts; and generated or enhanced poverty in short time, due to loss of agricultural fields and reduced fisheries yields [1,6,17,18].

2.1.1 Brazilian Amazonian reservoirs

Most of the previous published scientific studies dealing with large reservoirs and fisheries in Brazil address the Paraná-Paraguay River Basin, which is located in south Brazil and has the largest number of reservoirs and the most intense economic activity in the country [7,8,9,19]. The Amazon Basin has by far much less reservoirs in operation, which have been also less intensively studied than reservoirs in the south. However, there are several reservoirs being planned to be built in Amazon region in the near future as part of government development policies, some of which are already generating intense social and political conflicts [2,3,4]. We focused on reservoirs in Brazilian Amazon due to two main reasons. First, as already mentioned in a previous review, most of the information about these reservoirs is in unpublished thesis and reports, most of which being of limited assess [1]. In this sense, an updated review, bringing data both from the literature and empirical research, could thus contribute to identify gaps on information and summarize the major advances on reservoirs' ecological and social effects. Second, the Amazon River Basin, most of which is located in Brazil, have some of the largest and most pristine freshwater and forest ecosystems in the world. Amazon rivers sustain diverse and important small-scale fisheries [20] (see bellow), which can be severely disrupted by careless planned reservoir development [17,21]. Therefore, in Brazilian Amazon there is still the opportunity to protect large regions of rivers, aquatic habitats and associated fisheries, while unfortunately in Brazilian south most of the major rivers are already severely damaged by impoundment, pollution and deforestation [17]. This review should thus contribute to the evaluation and mitigation of reservoirs' impacts on Amazon fisheries.

2.2 Brazilian Amazon fisheries: a brief overview

Amazon people rely mostly and sometimes solely on fisheries as their main source of animal protein. Most of these fisheries are made by small-scale fishermen, using simple techniques, such as small boats, gillnets and hook and line [1,17,20,22,23]. These Amazon fishermen have been culturally defined as *caboclos*, or descendants from Portuguese and indigenous Brazilian [24,25]. Although *caboclos* may practice small-scale agriculture and ranching, fishing is often their main economic activity [25,26,27]. Amazon fishermen exploit many fish species in several aquatic ecosystems, such as floodplain lakes, tributary rivers, large rivers, seasonally inundated forests and, more recently, reservoirs [1,17]. Amazon fisheries are also linked to seasonal ecological changes on aquatic habitats (flooding periods) and fish behavior, due to variations on river water levels: during the low water season fish is more easily caught and fishing is more intense in lakes where fish are confined, while during high water season fishermen usually exploit the inundated forests or migratory fish that are moving along the main river channel [23]. Sometimes fishermen may even reduce fishing intensity during the high water season, turning to alternative activities, such as hunting, farming or wage labor in nearby cities (if available) [26,27].

Although the Amazon Basin has a highly diverse fish fauna with over 1,000 species, most of the food fish landings, (with exception of ornamental fisheriesconsists of about 40 fish species, including those usually found in lakes, from families Cichlidae, Sciaenidae and Osteoglossidae, as well as fishes inhabiting mainly rivers (lotic waters), from the families Pimelodidade (catfishes) [17,20,23,28,29]. Floodplains, which consists of a downstream portion of a large river and the seasonally flooded adjacent lowland forests and lakes, is one of the most productive and important ecosystems for Amazon fisheries. Fishing yields are usually higher on floodplain regions, especially on floodplain lakes, which may also have preferred commercial fishes [20,22,23,25,30]. Due to this higher fishing productivity of floodplain lakes, conflicts has arisen between local fishermen and outside fishermen from large cities, which has driven initiatives of fisheries management and control of lakes by fishing communities, restricting or preventing lake use by outsiders, through co-management systems [25,30,31].

2.3 Tucuruí reservoir and the Lower Tocantins River

Besides the overview of published studies on Amazon reservoirs, we addressed in more detail the Tucuruí reservoir's effects on fish and fisheries at the Lower Tocantins River. We selected this study case for two reasons. First, Tucuruí is one of the largest and most studied reservoirs in the Brazilian Amazon (Table 1), and one of the few that have available pre and post impoundment data and a longer series of data collection on fish and fisheries both in the reservoir and in the river upstream and downstream from the dam [13,21,22,32,33,34,35]. Second, we have recent empirical data from field research [36,37], to be compared to such previous published information.

The Tucuruí reservoir flooded a large area (Table 1) of the Tocantins River, a 2750 km long clear water river, which drains a region of 343000 km2 of the Araguaia-Tocantins River Basin. This river basin drains a large region of tropical forests and Brazilian savannas (*cerrado*), which has been subjected to several environmental changes, such as deforestation, intensification of recreational fisheries (Araguaia River) and dams (Tocantins River) [21].

We analyzed and summarized the results of a recent survey of the less well known fisheries and fish communities at a Lower Tocantins River region, downstream of the Tucuruí reservoir, between the coordinates of 02º50'944"S; 49º45"511"W and 03º06'210"S; 49º37'872"W in a region of floodplain (seasonally inundated islands and forests) with tributaries of Tocantins (locally called *igarapés*) and shallow floodplain lakes (locally called *lagoas*), between the town of Baião and a small fishing community (Xininga) [36]. Contrarily to the Tucurui reservoir, where a new fisheries developed, conducted mainly by migrant fishers from other Brazilian regions [1,21], the fishermen at the studied Lower Tocantins River region are *caboclos*, who have been living and fishing there from several generations and from before the river impoundment [22]. One of the authors (RAMS) sampled fish in floodplain lakes through experimental fishing using gillnets of different mesh sizes, in a total of 60 samples in 12 lakes (five samples of one day each per lake, with a mean duration of 7.8 ± 0.9 h per sampling). During fish samplings fishes were individually weighted, measured in standard length (cm) and some individuals of each species (random sampling) were analyzed for reproductive status (visual inspection of gonads' development).

Information on local fisheries was gathered through two complimentary methodologies:

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interviews with 300 local fishers (243 men and 57 women) in eight communities scattered along the Lower Tocantins region, including two districts of the town of Baião; sampling of 602 fish landings during 67 days in five of these small fishing communities. This research was conducted during the four hydrological seasons of that region: flooding, high, receding and low water, from 2006 to 2008. More detailed information on methods and results of these surveys are in [36,37]. We also analyzed 118 fish landings sampled in the market of the town of Baião (we selected only those landings sampled during the same days when we sampled fishing communities) by the staff of Eletronorte, the company that runs Tucuruí reservoir.

3 Large reservoir effects on fish and fisheries

3.1 Main ecological changes on Amazon fish and fisheries

According to research conducted mostly in rivers at the southeastern and northeastern Brazil [1,7,8,9,10], the main effect of dams on fish communities is a remarkable reduction or even regional extinction of large migratory fish species after reservoir filling. This may result from four major ecological changes caused by reservoir in aquatic ecosystems: first, the dam blocks the upstream reproductive migrations of adults, which cannot reach suitable spawning grounds. These fishes usually concentrate in the vicinities of the river downstream of the dam, where they may be heavily exploited by fishermen. Second, even if fishes can surpass the dam and be able to spawn upstream, the reservoir and the dam may be a barrier to the downstream dispersal of larvae and juveniles to the floodplain nursery sites located downstream of the dam. Third, even for those fishes that can complete their migration and reproduction in the river downstream of the dam, the retention of sediments and nutrients by the reservoir may reduce the water quality and quantity, thus reducing food supply (detritus) or increasing water transparency and the risk of predation. Fourth, alterations in the natural flooding regime due to reservoir's operation may prevent fish to enter spawning and nursery grounds [1,7,8,9,10]. Measures to counteract these impacts, such as passages in the dams to allow reproductive fishes to continue migrations upstream, are not always effective, nor necessary [7,10].

In floodplain's rivers, such as those in the Amazon, fish behavior, reproduction and feeding are usually intimately related to the flooding regime and flood pulses, which allow fishes to enter the inundated forests seeking shelter and food [38]. Considering that most Amazonian fishes rely on floodplains and some important commercial fishes are migratory [11,28], the reservoir impacts above described have been also observed in Amazonian impounded rivers (Table 1). Available surveys indicate changes on fish species composition after impoundment, including an increase on the abundance of some fishes. Although being considered as migratory, the mapará (*Hyphophtalmus* spp.) possibly do not require extensive migrations to reproduce and increased in abundance in the Tocantins River downstream from Tucurui reservoir [21] and in Samuel reservoir [39]. Non-migratory species adapted to lakes, such as tucunarés (*Cichla* spp.) and piranhas (*Serrasalmus* spp.) proliferated in Balbina and Curuá-Una reservoirs [40,41]. Albeit much less studied than in south Brazilian reservoirs [7,10], available evidence indicates that fish passages may be not effective as a fish conservation tool in Amazon dams. For example, fish ladders the Lajeado dam, Tocantins River, do not allow the downstream movements of larvae and juveniles of fish spawning upstream, possibly due to unsuitable reservoir conditions [42].

Reservoirs' effects on local fisheries and on fishermen have been observed in the literature for the Brazilian Amazon, especially for the better known Tucuruí reservoir [1,3,17,18,21,22]. However, usually such socio-environmental and economic effects have been supported by fewer empirical data and have been far less studied and less understood than reservoirs' effects on fish communities (Table 1). Effects of Amazonian reservoirs to fisheries vary according to the fish species exploited and reservoirs' location. In the reservoir itself, fish production has usually increased after impoundment, being sustained by an increase on some commercial fishes, such as tucunarés and mapara [21,39,40]. Albeit profitable, promoting even the recreational fisheries and touristic industry [43], such reservoir fisheries are usually not conducted by local fishers who exploited the region before the impoundment [17] and may be not sustainable in the long term [1,21]. In the region upstream from the dam the fisheries have been usually maintained or even enhanced, as long as there are sufficient river stretch, tributaries and floodplains to sustain fish migrations [1,21]. However, as already observed in impounded rivers at south Brazil [8,9], downstream from the dam the reservoir effects on migratory fishes are more pronounced. Consequently, fisheries downstream from the dam trend to be negatively affected, mostly due to the lack of migratory commercial fishes, reduced nutrient inputs and alteration of flooding regime, such as have been observed in the Tocantins River [1,17,21,22].

Table 1. Summary of information from published studies on fish and fisheries in Brazilian Amazon reservoirs. References are in the footnote.

Reservoir (Year filled), River	Area (Km2)	Capacity (MW)	Studies on fish and fisheries
Tucuruí (1984), Tocantins [a]	2430	3960	* Reduced abundance of migratory species. * Increased fisheries yields: reservoir and upstream * Decreased fisheries yields downstream * Local fishermen's knowledge about fish
Balbina (1987), Uatumã [b]	2360	250	* Reduced fish diversity in the reservoir * Increased abundance of a commercial fish species and enhanced fishing activity in the reservoir
Lajeado (2002), Tocantins [c]	630	90.25	* Fish ladders promote only upstream migration of adult fish * Changes on fish species composition in reservoir: less detritivores and fugivores, more piscivores
Samuel (1988), Jamari [d]	540	216	* Decreased fish diversity and, intensification of fishing in the reservoir
Curuá-Una (1977), Curuá-Una [e]	78	40	* Reduced Oxygen, less omnivorous and more piscivores in the reservoir

[a] 1,3,13,15,17,18,21,22,32,33,34,35,36,37,44,45
[b] 40,43
[c] 42
[d] 4,39
[e] 5,41

3.2 Effects of Tucuruí reservoir on fish and fisheries in the Lower Tocantins River

Data gathered by our research project confirmed and updated previous information about the fish and fisheries of the Tocantins River downstream from the dam (Table 1). As mentioned in previous surveys during the years following impoundment [1,21,22], our results confirmed that fisheries yield were drastically reduced in the Lower Tocantins River: the estimated total annual catch, considering both urban market (Baião town) and the five fishing communities studied (199.3 t) [36] was four times lower than the total annual catch (858 t) recorded in the Tocantins River upstream from the reservoir during 1988 [35] and 1.3 times lower than the total annual catch (251.7 t) reported in the same region of the Lower Tocantins River before the impoundment [22]. The daily total fish production we recorded after the impoundment was of 106.2 kg in villages and 189.2 kg in the urban market [36], while before the impoundment daily production was 116.7 kg and 3,333.3 kg respectively for one fishing community and urban markets [22]. The mean catch per unit of effort (CPUE) recorded for the urban market in our survey (48.6 kg x fishers $^{-1}$) [36] was similar to that recorded in the same region in 1981, before the closure of the dam (20 to 40 kg x fishers $^{-1}$ depending on month) [22], indicating that fisheries are still an important economic activity in the Lower Tocantins, 26 years after impoundment. However, fishers may have been maintaining such CPUE through an intensification of fishing effort, besides buying fish from other fishers, which can cause overfishing.

Former studies mentioned that fisheries in the Lower Tocantins after the impoundment were exploiting the fish mapará, which seemed to be less affected by the reservoir, while the catches of the migratory curimata (*Prochilodus nigricans*) decreased [21]. According to our recent results the most caught fish species in the Lower Tocantins were the mapará, curimata and pescada (*Plagioscion squamosissimus*) both in the fishing communities and the urban market [36]. Therefore, it seems that curimatá populations were able to cope with the

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reservoir induced changes and fisheries recovered after some years. Indeed, the corimbata (*Prochilodus lineatus*), a similar fish species is usually one of the main species caught in south Brazilian reservoirs [1,7,8,19]. The corimbata may persist in the reservoir and adjacent river if it can migrate and spawn in a free flowing river stretch or in tributary rivers without dams [8]. Conversely, as proposed for Amazonian rivers, including the Tocantins River, the abundance and hence the fisheries of large migratory catfishes (Pimelodidae) were possibly reduced due to impoundment, because the dam impede both adults from migrating upstream and larvae from drifting downstream [11]. Catfishes from 10 species (mainly dourada, *Brachyplatystoma rousseauxii*, filhote, *B. filamentosum*, piramutaba *B. vaillantii*, peixe galinha, *Pimelodina flavipinnis*, surubim, *Pseudoplatystoma fasciatum*, among others) accounted for only 4 % and 2 % of the total fish biomass landed respectively at the urban market (10.3 t) and fishing communities (6.9 t) studied recently (2006 to 2008) in the Tocantins River downstream from the dam [36]. This indicates possible negative reservoir effects to the valuable catfish fisheries in Amazonian rivers [28]. Furthermore, because large catfishes are the main top predators in these rivers [29], a decrease in abundance of catfishes could also cause ecological changes on fish communities, but such ecological effects remain largely unknown.

Most of interviewed fishers (267 of 300) from eight communities of the Lower Tocantins River, mentioned that the impoundment reduced fish abundance in the Tocantins River. The jaraqui (*Semaprochilodus brama*) was the most cited fish (208 fishers) that was reduced in abundance after the reservoir filling [37]. This fish was not caught by fishers in our recent survey conducted from 2006 to 2008 [36], but it is still caught and sold by fishers from the Tocantins River upstream from the dam [35]. Considering that jaraqui is an important commercial and migratory fish in other Amazonian rivers, such as Negro River [46], it is possible that the dam has disrupted the fisheries of this fish species in the Lower Tocantins River. When asked about fishes that could have increased in abundance after impoundment, 70 and 48 interviewees mentioned respectively pescada and curimata. These interview results did agree with results from sampling of fish landings and fish communities (see above).

3.3 Environmental and social factors alleviating reservoirs' impacts in the Lower Tocantins

Our research results indicated that, at least some impacts of Tucuruí reservoir to small-scale fisheries, such as the decrease in yields and changes on fish catch composition [36,37], were observed in the Lower Tocantins region near Baião town, which is located about 140 km downstream from the dam. According to interviews, fishers are well aware of these reservoir's impacts, but Brazilian current legislation does not allow for any kind of compensation to them, as the studied region is considered outside the area influenced by the reservoir. This situation has stimulated conflicts between fishers and reservoir managers, besides leaving these small fishing communities in disadvantage to deal with shortages in fish supply.

However, fisheries are still a viable economic activity in the Tocantins River downstream from the dam, exploiting mainly those fish species that were less affected by the reservoir and has medium to large size, such as curimata [36]. Therefore, what could be done to alleviate reservoir impacts and improve or at least maintain fish yields in the Lower Tocantins River? A compound problem is that, besides the reservoir, fisheries there have been subjected to other detrimental factors, such as deforestation (leading to habitat degradation) and increased fishing pressure [21].

A possible factor allowing the persistence of fisheries in this region may be the floodplain with several lakes, which are important fish spawning sites, according to both fishers and biological data. Fish samplings recorded a total of 55 fish species spawning in 12 lakes, including the main commercial fishes (curimata, pescada and mapara). During a workshop held with local fishers near the town of Baião, we discussed the research results and asked fishermen to indicate priority sites to fish reproduction and to establish conservation areas in satellite images of the region. Nearly all the sites pointed by fishermen as important to fish spawning were floodplain lakes. Therefore, as observed in other impounded rivers [8], the maintenance of the ecological integrity of floodplain lakes seems to be crucial to avoid fisheries disruption in the near future. A feasible way to protect those floodplain lakes would be the co-management approach, such as the fishing agreements of accords, already adopted in other Brazilian Amazon regions, where fishers devise and implement rules restricting entrance to lakes and the intensity of fishing effort (kind and amount of gear) [25, 31]. Governmental and non-governmental institutions (NGOs) usually join the fishermen and support them in managing the local resources. This has happened in the Mamiraua Reserve, one of the most developed of such co-management systems, where fishermen have been successful in increasing the abundance of commercial fishes in managed floodplain lakes [30,47,48]. However, the Lower Tocantins River region differs in some respects from the Solimões River, in the Central Amazon, where Mamiraua is located [30]. The Tocantins River has a much larger population, more degraded landscape, impacts from reservoir and land use, besides the fact that Tocantins fishing communities are not so organized and do not have the financial resources that currently sustain the Mamiraua reserve. Therefore, co-management systems in the Tocantins River may have to be based on a more simple and feasible approach, such as the fishing agreements [31]. Indeed, some of the studied fishing communities are already organizing themselves and starting to devise management rules to protect lakes, but they need assistance of government institutions to maintain these initiatives. In Sri Lanka (Southeast Asia), local fishermen have also organized themselves in successful co-management initiatives to regulate reservoir fisheries and to prevent overfishing [49].

Finally, besides the knowledge gaps regarding fish reproductive and migratory behavior, which has been also mentioned for other rivers [8,10,21], there is a more pronounced gap in knowledge about socio-economic factors related to fishing communities, such as fishing dynamics and fishers' local ecological knowledge about fish. Local fishers in the Amazon [50], including those in the Tocantins River [44,45], have detailed knowledge about fish ecology and behavior, which can be useful to assess changes on fish populations and potential ecological impacts, such as those caused by reservoirs. Besides providing new and useful biological information [50], such fishers' knowledge may be directly applicable to fisheries management [47]. Socio-economic impacts caused by Amazonian dams may affect directly the protein consumption of the local families, which is largely based on fish [51].

4 Conclusion

The survey in the Lower Tocantins highlights that effects of a large dam may extend far beyond the reservoir itself and fishers have knowledge about such reservoir effects on aquatic environments. Nevertheless, fishermen and fisheries have been not addressed with detail in previous impact assessments and scientific surveys related to river impoundments in Brazilian Amazon. It should be noted that most of the Amazon reservoirs (Table 1) were implemented before 1990, a period of military government in Brazil, when decisions were not democratic and environmental impact surveys were not required [3,18]. Fortunately, now environmental impact assessments are mandatory to reservoirs in Brazil and more recently, some of these assessments have been addressing fisheries and fishermen. However, the efficacy of the system of environmental impact evaluation in Brazil has been criticized [2,4]. We suggest that future research on fishing dynamics, including fish landing data on a more continued temporal basis, studies on fishermen knowledge about fish and studies on the interaction of local livelihoods with local resources, would improve the current knowledge about reservoir influences on small-scale fisheries both in Amazon and elsewhere.

Besides electric energy, reservoirs may provide other benefits, such as fishing, tourism, water provision and even reduced pollution downstream [1]. However, such benefits should be balanced against potential negative effects of energy production through large reservoirs to both fish and fishermen. Such socio-economic and ecological impacts of dams and reservoirs should be better acknowledged and considered in political and economic decisions regarding energy issues, in Brazil and elsewhere and especially in tropical developing countries, such as those in Africa and Asia [6,49].

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