'From the sky to the ground': fishers' knowledge, mapping and hydrological data indicate long term environmental changes in Amazonian clear water rivers

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Abstract

Fishers have detailed local ecological knowledge (LEK) which can contribute to track long term environmental changes in less studied tropical rivers. Our goal is to investigate the long-term environmental changes on hydrology (floods and droughts), water quality and landscape in three clear water rivers in the Brazilian Amazon. We also aim to compare the three studied rivers, which represent a gradient of severity of environmental changes, from the more pristine Trombetas, followed by the Tapajós and the more impacted Tocantins. We conducted individual interviews with 129 fishers (67 in Tapajós, 33 in Tocantins and 29 in Trombetas), analyzed land cover through maps produced by the project MapBiomas, and analyzed hydrological data from the Brazilian National Water Agency. The results of three distinct data bases analyzed here (mapping, hydrological data and fishers' knowledge) indicated environmental changes in the studied rivers. The maps clearly show a gradient of anthropic changes, from the more pristine and less altered Trombetas river, the moderately altered Tapajós and the more intensely changed landscape in the Tocantins River. Fishers from the Tocantins River mentioned a greater variety of negative changes in water quality related to anthropic actions, such as dams, deforestation and pollution. Moreover, most fishers indicated hydrological changes making the Tocantins River drier in more recent years ('drying more and filling less'), which would cause negative effects on fish. In the Tapajós River fishers mentioned more varied hydrological patterns and negative effects on water quality linked to mining, whereas in Trombetas fishers perceived increased floods, which may be related to climatic changes. The fishers' knowledge was a useful and unique source of 'on the ground' detailed data about long term changes in tropical rivers.

Key-words: local ecological knowledge, environmental impacts, small-scale fisheries, climatic changes, dams, landcover changes

Introduction

The Indigenous and local people (IPLC) accumulate a detailed knowledge about the ecosystems, animals and plants with which these people interact in a daily basis, and this knowledge can be considered as Indigenous, traditional or local ecological knowledge (Berkes, 1999). This body of knowledge held by the IPLC is culturally transmitted through generations, (Berkes, 1999), hence providing a unique and invaluable perspective about long term environmental changes (Huntington 2011). The studies on fishers' LEK have provided many useful data on fisheries and fish ecology, including, but not limited to, migratory movements, feeding habits, reproduction and patterns of use of fishing resources (Silvano & Begossi, 2010; Herbst & Hanazaki, 2014; Nunes et al., 2019; Fogliarini et al., 2021). Furthermore, studies on fishers' LEK may provide unique or hard to get information about the past status of aquatic ecosystems and species, thus tracking changes caused by environmental impacts, such as dams (Hallwass et al., 2013; Runde et al., 2020; Santos et al., 2020) and management measures, such as protected areas (Hallwass et al. 2020). Moreover, fishers' LEK go beyond fish and may include knowledge about tides, currents, hydrology, or changes in rivers' flooding dynamics (Esselman & Opperman 2010; Guerreiro et al., 2016; Langill & Abizaid, 2020, Rasekhi et al. 2022). More recently, fishers' LEK has been successfully integrated with analytical tools and approaches from ecological science, including stable isotopes to study fish diets (Pereyra et al., 2021), interaction networks (Pereyra et al., 2023), modeling of fish habitat distribution (Lopes et al. 2018), satellite imagery and geographical information systems (Aswani & Lauer 2006; Schmitz Nunes, et al. 2021), among other approaches (Loch & Riechers, 2021).

The Amazon Basin is the largest and more pristine river basin in the world, including also the richest diversity of freshwater fishes (Tedesco et al., 2017; Goulding et al., 2003). Nevertheless, most of the environmental policy and research about the Amazon has focused mostly on terrestrial forests, not properly recognizing the relevance and problems associated with biodiversity, fisheries and local people in Amazonian aquatic ecosystems (Castello et al. 2013; Lopes et al. 2021). Notwithstanding the recognized relevance of the forest cover in the Brazilian Amazon to the maintenance of the hydrological cycle (Trancoso et al., 2010) and even fish and fisheries (Arantes et al. 2018, Capitani et al. 2021), there is a gap in the establishment of conservation polices and protected areas tailored to aquatic ecosystems (Dagosta et al., 2020; Keppeler et al. 2018).

As observed for other freshwater socioecological systems worldwide (Fluet-Chouinard et al. 2018; Funge-Smith & Bennett 2019), people living in the Brazilian Amazon rely heavily on natural resources for their livelihoods, including mostly fish (Hallwass and Silvano 2016). The fish consumption in some regions of the Brazilian Amazon can reach up to 60 kg of fish per person (Isaac & Almeida, 2011), being among the largest consumption rates worldwide, thus evidencing the importance of aquatic ecosystems, fish and fisheries for the food security of Amazonian riverine people (Isaac et al., 2015; Begossi et al., 2019). Besides providing affordable and varied animal protein to local people (Heilpern et al. 2021), the small-scale fisheries are also a relevant and needed source of income to Amazonian people (Isaac & Almeida, 2011; Hallwass and Silvano 2016).

The natural flood pulse associated with the seasonal variation of rivers' water levels and periodic inundation of riparian forests is an important ecological characteristic in Amazonian floodplain rivers, sustaining fish production and associated fisheries (de Mérona & Gascuel 1993; Isaac et al., 2016; Barros et al., 2021). The regular periods of low water (droughts) and high water (floods) occur naturally and are important to the maintenance of the Amazonian ecosystems, to the extent that animals, plants and people living along river margins have adapted to these seasonal hydrological variation (Junk et al., 1989; Junk & Piedade, 1993; Gram et al., 2001; Nagl et al., 2021). The multiple environmental changes experienced by the Amazon basin and driven by anthropic influences, such as deforestation, climatic change and river fragmentation by dams, can disrupt the natural hydrological cycle, alter the flood pulse and affect the dynamics of floods and droughts (Marengo & Espinoza, 2016; Winemiller et al. 2016). Indeed, extreme droughts and floods had occurred more often along the last decades in the Amazon Basin, linked to large scale deforestation, climatic changes and dams for hydroleletricity, which has detrimental effects to both aquatic ecosystems and local riverine people (Aragão et al., 2008; Castello et al., 2015; Marengo et al., 2016; Souza et al., 2019; Gatti et al., 2021). For example, dams in Amazonian rivers can alter the water quality and lead to river fragmentation and disruption of fish migratory routes (Nunes et al., 2019; Winemiller et al., 2016; Hallwass et al., 2013), among other detrimental effects to the hydrological cycle (Swanson et al., 2021; Figueiredo et al., 2021).

The clear water rivers in the Brazilian Amazon have a unique fish diversity, ecological interactions between fishes and forests and widespread small-scale fisheries, but these rivers are threatened by development projects, such as dams for hydropower generation, and had been less studied and had received less consideration from policy makers (Silvano & Hallwass 2020; Runde et al. 2020, Capitani et al. 2021; Nagl et al. 2021; Pereyra et al. 2023). The Tocantins-Araguaia river basin is considered to be among the most degraded river basins in the Amazon (Pelicice et al., 2021; Swanson et al., 2021), being affected by deforestation and by the establishment of seven dams for hydroeletric power generation along its main course (Zahar et al., 2008; Timpe & Kaplan, 2017; Pelicice et al., 2021). There are currently two more development projects planned to be implemented in this river, which will alter the river rapids (Akama, 2017) and threaten the fish, fisheries and endemic aquatic species, such as the river dolphin, *Inia araguaiensis* (Hrbek et al., 2014). The Tapajós River is currently free of dams in its main course, but there are more than 90 planned dams to be built in this river basin, which makes it one of the most threatened rivers in the Brazilian Amazon regarding development projects (Latrubesse et al., 2017; Fearnside, 2015a, 2015b). These planned dams can reduce availability of fish for local people along the river (Runde et al. 2020), in addition to flood protected areas and indigenous lands (Fearnside, 2015a). Another impending environmental problem in the Tapajós river basin is the gold mining activity (Bidone et al., 1997; Lino et al., 2018). The small-scale gold mining has intensified in Latin

America and in the Brazil since the 1980s (Malm, 1998; Nevado et. al., 2010), affecting the Amazonian rivers through deforestation, increased sediment loads and the contamination by mercury (Hg), which is used for gold extraction (Sousa & Veiga, 2009; Tudesque et al., 2012; Fernandes et al., 2014; Lobo et al., 2015). In the rivers' waters, the mercury can go through a process of methylation by bacteria, generating the methylmercury, which is the most toxic form of Hg and that can penetrate in aquatic organisms and bioaccumulate along the aquatic food chains (Ullrich et. al., 2001; Nevado et. al., 2010). The mercury contamination has been observed in fish and people along the Tapajós River (Lino et al., 2018; Vasconcellos et al., 2021). The Trombetas River is less altered, albeit less studied than the other two rivers. This river has 92.5% of its basin covered by protected areas and indigenous lands (Trancoso et al. 2010). The population of the Trombetas River is highly dependent on fish for animal protein consumption (Isaac et al. 2015).

Our goal is to investigate the long-term environmental changes on hydrology (floods and droughts), water quality and landscape in three clear water rivers in the Brazilian Amazon, through complementary analyses of mapping, hydrological databases and fishers' LEK. We also aim to compare the three studied rivers, which represent a gradient of severity of environmental changes, from the more pristine Trombetas, followed by the Tapajós and the more impacted Tocantins. Therefore, we would expect more evidence of changes in the Tocantins and less in the Trombetas rivers. Finally, we analyzed fishers' LEK about the influences of the hydrology on fish in the three rivers.

Methods

Study area

We conducted this study in the middle reaches of the rivers Tapajós, Tocantins-Araguaia (hereafter Tocantins) and Trombetas, in the Brazilian Amazon (Fig. 1). These three rivers are clear water rivers, due to the low concentration of nutrients and suspended sediments in their waters (Sioli 1950; Junk et al., 2011).

The Tocantins River has more than 2,400 km of length (Goulding, 2003) and its drainage area includes the Araguaia River, forming the Tocantins-Araguaia River Basin (ANA, 2022). Approximately 19 % of vegetation cover of the Tocantins-Araguaia River

Basin was deforested along the last years, causing an annual increase of 24 % in the water discharge and anticipating in about one month the seasonal flood peaks, due to a reduction in evapotranspiration during the rainy season (Costa et al., 2003; Trancoso et al., 2010). Although this study included one community located in the Araguaia River (Fig. 1), for convenience hereafter we will refer to it as Tocantins River. The rising and high-water periods in the Tocantins River occur from October to April, whereas the receding and dry water periods occur from May to September. We studied four fishing communities in this river (Fig. 1, Table 1): Vila Tauri, Espírito Santo, Apinajés and Santa Cruz (located in the Araguaia River).

The Tapajós River has 851 km of length (Goulding et al., 2003). The rising and high-water periods in the Tapajós River occur from January to June, whereas the receding and dry water periods occur from July to December. We studied nine fishing communities in this river: Cupari, Cauaçuepá, Brasília Legal, Barreiras, Pedra Branca, Miritituba, Canaã, São Luís do Tapajós and Pimental (Fig. 1, Table 1).

. The Trombetas River has approximately 750 km of length and most of its river basin drains Amazon rainforest. The rising and high-water periods in the Trombetas River occur from March to August, whereas the receding and dry water periods occur from September to February. We studied four fishing communities in this river: Varjão, Muçurá, Tapagem and Cachoeira Porteira (Fig. 1, Table 1).

The riverine people in the Amazon live along the shores of major rivers and lakes; these people regularly use the rivers for navigation, water provision and the biodiversity of these aquatic ecosystems sustain their livelihoods, as most of the animal protein consumed is derived from small-scale fisheries (McGrath et al., 2008; Isaac & Almeida 2011; Begossi et al., 2019).

Interviews

We gathered data on fishers' knowledge and perception through individual interviews with fishers following a standardized semi-structured questionnaire (Appendix 1, Suppl. Mat.), which included questions addressing fishers' perceptions on changes in the droughts, floods and water quality, since the onset of fishing activity of each interviewee. These questions are a subset of a more complete questionnaire to gather more detailed data for other studies (Runde et al. 2020; Silvano & Hallwass, 2020). We conducted interviews with 67 fishers in nine communities in the Tapajós River, and 33 fishers in four communities in the Tocantins River from September to November 2018, plus 29 fishers in four communities in the Trombetas River, in September 2019 (Table 1).

Upon arrival in a studied community, we first talked to community leaders to explain the purposes and goals of the research and asked for his or her permit to conduct the research in the community. After getting the permit, we asked leaders to indicate some of the more experienced or active fishers in the community to be interviewed. These more experienced fishers are usually those who catch more fish or go fishing more often (Nunes et al. 2019). After interviewing the indicated fishers, we asked those fishers to indicate other experienced or active fishers who could be potential participants in the research, thus following the snowball sampling methodology. This methodology, which consists in generating reference networks to assess members of a specific group that fits given research criteria (Berg, 2006), has been adopted in previous studies addressing fishers' knowledge (Silvano et al., 2006; Hallwass et al., 2013; Runde et al., 2020).

This research was approved by the ethics committee of the Federal University of Rio Grande do Sul (CONEP/CAAE: 82355618.0.0000.5347).

We made visual comparisons of percentages of categories of answers to questions related to water quality and hydrological cycle among the three studied rivers. We compared the mean interviewees' age among the three studied rivers through Analysis of Variance (ANOVA). We also compared the mean number of distinct answers (citations) provided by each interviewed fisher related to changes in water quality, causes for such changes and changes in droughts and floods among the three studied rivers through Kruskal-Wallis, as these data were no normally distributed, usually ranging from none to two citations per fisher.

Landscape analysis

We used maps and data on land use and land cover from project MapBiomas - Coleção 7 (MAPBIOMAS, 2023) to evaluate the temporal change on coverage of forest (natural cover) and anthropized areas in each river (Fig. 2). These maps have precision of 30 m, as each pixel in the image measures 30 m on each side, or 900 m². We evaluated the landscape of the three rivers based on these maps on three years: 1985, 2000 and 2019 (the more recent year and close to the years when interviews were made).

The land cover classification adopted in the MapBiomas platform has both broad and more specific categories of land cover and land use in Brazil, ranging from anthropic uses to natural formations (see mapbiomas.org). Here we adopted a broader classification including three categories: natural formation (mostly forest), anthropic areas (deforested area or exposed soil, agriculture or buildings) and water, to check for potential changes in land cover across time in the three studied rivers.

After the reclassification of maps of each studied year and river, according to the land cover categories, we plotted the points of studied communities and drawn a vetorized line joining the community points. We then stipulated a 20 km buffer around this line and calculated the proportions of land use categories within this continuous buffer (Fig. 2). We made all procedures of landscape analyses by using the geoprocessing software QGIS (version 3.28.4 Firenza).

Rivers' water levels

We obtained data on altimetric variation in water levels of the studied rivers from the platform HIDROWEB, from the Brazilian National Water Agency (Agência Nacional de Água, ANA). These data were gathered from one fluviometric station in each river, as each station send daily measures of water level. We evaluated measurements taken from 1985 to 2019, by comparing three time periods (1985 – 1996, 1997 – 2008, 2009 – 2019), to check for possible changes in water level patterns among these three time periods. For each time period, we calculated an average monthly mean per year (points in Fig. 3). Each data point corresponds to the monthly mean for each year, hence the dispersion of points from the same time period (color) indicates the variability in the river water level during that period (Fig. 3). Furthermore, we also calculated the overall mean in water level for each month for each time period (lines in Fig. 3), considering all years during that time period.

Results

We interviewed 67 fishers (63 men and four women)in the Tapajós, 33 fishers (28 men and five women) in the Tocantins, and 29 fishers (26 men and three women) in the Trombetas. The interviewees' age varied from 25 to 78 years with a mean age of 47 years in the Tapajós; from 26 to 82 years, with a mean age of 56 years in the Tocantins; and from 31 to 78 years with a mean age of 51 years in the Trombetas: fishers are older in the Tocantins compared to the Tapajós ($F_{2,\ 124}$ =5.2, p <0.01, Fig.S1). The mean fishing experience (years since started fishing) of the interviewed fishers were 25.5 years (± 11.9 years) in the Tapajós, 34.8 years (± 17.6 years) in the Tocantins and 38.3 years (±16.4 years) in the Trombetas.

Changes in water quality

Changes in water quality were perceived by 91%, 70% and 72 % of fishers interviewed respectively in the Tapajós, Tocantins and Trombetas rivers. The interviewed fishers reported up to 12 categories or kinds of changes in water quality in the three rivers, and the most cited change was dirtier waters, especially in the Tapajós (Fig. 4). Indeed, other cited changes, such as muddy water (the second most cited), as well as yellowish, greenish or dark waters (Fig. 4) can be also related to more turbid waters nowadays compared to the past. The average number of kinds of changes in water quality mentioned per fisher did not differ among the three studied rivers. Altogether, the interviewed fishers in the three rivers cited 16 potential causes for the observed changes in water quality, the main ones being mining in the Tapajós, droughts in Trombetas, and dams, deforestation, floods and pollution in the Tocantins (Fig. 5). There was no difference among the three studied rivers in the number of kinds of changes in water quality mentioned per fisher (H=3.39, df= 2, p = 0.18, Fig. S2), neither in the number of causes of changes in water quality mentioned per fisher (H=3.3, df= 2, p = 0.19, Fig. S3).

Changes in hydrology (floods and droughts)

Changes in the hydrological regime of floods and droughts were reported by all interviewed fishers in the Tocantins and by 84 % and 86 % of interviewed fishers respectively in the Tapajós and Trombetas. The interviewed fishers mentioned variable patterns in the

Tapajós, including both declines and increases in floods and droughts; a decrease in the hydrological variation and amplitude of the flood pulse in the Trombetas (drying less, filling less), and a drier river in the Tocantins, which according to fishers is filling less and drying more (Fig. 6). The average number of kinds of changes in the hydrological regime did not differ among the three studied rivers ($H= 0.58$, $df = 2$, $p = 0.75$, Fig. S4)

Effects on floods and droughts on fish

The droughts influence fish according to 96%, 73% and 93% of the interviewed fishers respectively in the Tapajós, Tocantins and Trombetas. Similarly, floods should influence fish according to all interviewed fishers in the Trombetas and most (94%) of the interviewed fishers in the Tapajós and Tocantins.

Overall, fishers from the three rivers mentioned up to 16 potential effects of droughts on fish (Fig. 7). Although fishers mentioned a positive effect of droughts on fisheries by facilitating fish catches, most of the mentioned effects are negative, such as increased fish mortality linked to drying lakes, fish trapped in drying water, lack of food for fish, and fish population declines, especially in the Tocantins River (Fig. 7). Fishers from all three rivers, but especially those in the Tapajós and Trombetas rivers, mentioned also that water gets warmer during droughts (Fig. 7).

The interviewed fishers mentioned up to 17 effects of floods on fish, most of which are positive and associated with increases in fish abundance and facilitation of reproduction, spawning and feeding (Fig. 8). Moreover, many interviewed fishers from all studied rivers mentioned that during floods fish would enter the flooded forest (called *igapó* in Portuguese) and feed in this habitat. Contrarily to droughts, floods would negatively affect fisheries by making it more difficult for fishers to catch fish (Fig. 8).

Landscape and hydrology

The temporal patterns in land cover revealed by the maps from the MapBiomas project indicated a gradient of environmental change ranging from the more altered Tocantins River (Fig. 2a), the moderately altered Tapajós (Fig. 2b) and the more pristine and unchanged Trombetas (Fig. 2c). Considering the 20 km buffer surrounding the studied communities (Fig.

2), across the 34 years period from 1985 to 2019, 43% of the land cover in the Tocantins River had changed from natural (forest) to anthropic land cover (agriculture, roads), as natural formations covered 74% of buffer area in 1985, but only 32% in 2019 (Fig. 2a). In the same time period, the Tapajós had a decrease of 12% in natural formations, from 76% in 1985 to 64% in 2019 (Fig. 2b), whereas the Trombetas even showed a slight increase in natural area, from 86% in 1985 to 87% in 2019 (Fig. 2c).

Overall, the seasonal variation in water level was similar among the three time periods (1985-1996, 1997-2008 and 2009-2019) in the three studied rivers (Fig. 3), apart from a few variations. In the Tocantins, the mean level of water was lower during the flood in the more recent period and more extreme droughts (lower water levels) occurred in more recent years from 2009 to 2019 (Fig. 3a). In the Tapajós, the water level was somewhat higher year-round in the past years (1985-1996) compared to the two more recent periods, and extreme floods of up to 15 m of water appear only in the past years (Fig. 3b). In the Trombetas, the mean water level during floods has increased in the two more recent periods compared to past years, and the peak of floods seem to be anticipated by a month (Fig. 3c). Furthermore, in the Trombetas River, the mean water level was somewhat higher in recent years (2009-2019) compared to past years (1985-1996) throughout the receding water period, from July to September (Fig. 3c).

Discussion

Water quality

As observed in previous studies (Aswani & Lauer 2006. Esselman & Opperman 2010, Hallwass et al. 2013, Silvano et al. 2023) fishers' knowledge complemented well the two broader data sources, by indicating potential environmental changes in a more refined and local spatial scale. Contrarily to expected, the average number of citations per fisher of changes in water quality and hydrology and causes for such changes did not differ among the three studied rivers. This may be partially attributable to the low number of citations per fisher, usually one or two, and to the fact that nearly all fishers recognized changes in water quality and hydrological regime, even in the less impacted Trombetas and Tapajós rivers. However, fishers from the Tocantins River mentioned a greater variety of negative changes in water quality related to anthropic actions, such as dams, deforestation and pollution. Moreover, most fishers indicated hydrological changes making the Tocantins River drier in more recent years (‘drying more and filling less’), which would cause negative effects on fish. This fishers’ perception of a drying river agrees with the lower average water level and more extreme foods observed in recent years in the hydrological dataset. Therefore, all three data bases analyzed here indicated the intense anthropic changes and the series of environmental impacts experienced by the Tocantins River along the last decades (Pelicice et al., 2021).

The potential effects of river dams on the water quality were more cited in the Tocantins River. The seven dams and hydroelectric facilities along this river have altered the hydrological cycle, modified the flux of sediments and reduced the availability of nutrients in the river’s water (Zahar et al., 2008; Timpe & Kaplan, 2017; Pelicice et al., 2021). The retention of sediments makes the river downstream from dams less productive and more susceptible to soil erosion, altering the psycho-chemical properties of the water and increasing the water’s temperature, due to water release from the reservoir (Manyari & Carvalho, 2007; Timpe & Kaplan, 2017; Winton et. al., 2019). The retention of sediments and nutrients may partially explain the alterations in water quality (‘dirty water’) and coloration mentioned by the interviewed fishers in the Tocantins River, as the studied communities there are located both downstream and upstream of existing dams. The dams can also change the flood pulse of rivers, by altering the seasonality, the duration and intensity of flood pulses, as well as by causing unexpected floods and droughts, which may occur in unusual periods of the year (Manyari & Carvalho, 2007; Timpe & Kaplan, 2017). These changes in the flood pulse, coupled with a decrease in the sediment load, can reduce the availability of nutrients in the water (Timpe & Kaplan, 2017; Winton et. al., 2019).

A dam for hydropower production was built in 2015 in the Teles Pires River (Santos et al., 2022), which is an affluent of the Tapajós River located upstream from the studied region. The effects of some dams may cascade throughout the river basin (Winemiller et al., 2016). This may account for potential dam influences on water quality pointed by the fishers’ knowledge in the Tapajós River, even considering that this river currently has no dams along its main course. Moreover, there are projects of dams to be built in the Tapajós River (Fearnside 2015), which will threaten the aquatic biodiversity and small-scale fisheries

(Latrubesse et al., 2017, Runde et al. 2020).

Most of the interviewed fishers associated the decrease in the water quality to mining in the Tapajos River, which has one of the largest gold mining operations in Brazil, (Lobo et. al., 2017). Notwithstanding its economic relevance, the gold mining activity has caused several environmental impacts in the Tapajós River. The deforested areas, to clear mining sites and built roads to transport the gold, release organic matter in the rivers, hence increase suspended organic matter in the water, as well as changing water color, turbidity and acidity (Rodrigues et. al., 1994; Lobo et. al., 2016). Furthermore, the mercury, which is regularly used to separate gold from soil, can spill to the rivers' waters, bioaccumulate and contaminate fish and people (Lino et al., 2019; Vasconcellos et al. 2021). This chronic environmental problem of mercury contamination should decrease the overall water quality in the Tapajós River, as mentioned by the interviewed fishers, but this change cannot be readily deduced from the other two technical databases (maps and hydrology).

The fishers in the Tocantins River also mentioned that the deforestation could be related to changes in the water quality, which matches the landscape analysis that evidenced an intense deforestation in this river. Conversely, deforestation was not mentioned in the other two rivers, which have greater forest coverage. The deforestation in the Brazilian Amazon has increased in recent years and is estimated that this biome had lost about 20% of its original forest cover (Souza et. al., 2020). This loss of forest cover can alter the flood pulse in the rivers (Melack & Coe, 2021) and worsen the water quality through decrease in oxygenation, increases in the water temperature and soil erosion, which increase sediment loads and water turbidity (Neill et al., 2001; Restrepo et al., 2015; Ríos-Villamizar et al., 2017). The deforestation may be also related to river pollution, which was also mentioned by fishers in the Tocantins River as a potential cause to changes in water quality. The deforestation can be linked to forest fires, which release air pollution and residuals that may end up in the rivers (Oliveira et al., 2020; Ellwanger et al., 2020). The pollution may be also linked to agricultural activities and contamination of waters by pesticides, as mentioned by some fishers in the Tocantins River. These pesticides, and other chemical products rich in nitrogen and phosphorus used in the agriculture, may reach the rivers and cause eutrophication, reduced oxygen levels and contaminate food chains through bioaccumulation (Neill et al., 2001;

Castello et al., 2013). The river pollution may be also linked to an increased urbanization in the Amazon along the last decades, which lacks adequate infrastructure and hence can promote eutrophication, increased turbidity and suspended materials (Ríos-Villamizar et. al., 2017; Ferreira et. al., 2021).

Hydrological changes and their influence on fish

The fishers from all three rivers reported changes in floods and droughts now compared to when they started fishing. As quoted by a 60 years old fisherman in the Tapajós River: 'the floods and droughts, no one understands anymore'. The fishers' knowledge indicated a drying Tocantins River, which may be related to the existing dams along its course. The dams may reduce the variability of the flood pulse in the river downstream, due to the reduction in the flood area and in the amount of water released from the dam (Nilsson & Berggren, 2000; Poff & Hart, 2002), whereas upstream from the dam there could be an enhanced probability of unexpected floods (Prado et al., 2016). The increased droughts in the Tocantins River according to fishers' knowledge can be also related to the deforestation in this river and in the Amazon basin, as the evapotranspiration from the vegetation and the resulting precipitation are important to mitigate the effects of the dry season (Staal et al., 2018; Bagley et al., 2014). There could be feedback between deforestation and droughts, as deforestation increase the occurrence of droughts, which can further reduce forest cover through increased probability of forest fires (Zemp et al., 2017).

Conversely, in the Tapajós River there are not a marked consensus among fishers related to hydrological changes and fishers mentioned more floods in the Trombetas. Historically, periods of floods and droughts in the Amazon are related respectively to events of El Niño and La Niña and to the increase in Sea Surface Temperature (SST), which jointly regulate part of climatic variability in South America (Marengo et al., 2008). Historical records indicate the occurrence of one extreme climatic event (flood or drought) per decade (Marengo et al., 2011), but in the last years these extreme events have been recorded more often. In a 10 years period, the Amazon basin has been affected by four extreme droughts (in the years of 2009, 2012, 2014 and 2015) and by two extreme droughts considered to be the more drastic ones in the century, in the years of 2005 and 2010, which caused several socioecological impacts (Marengo & Espinoza, 2015). This higher intensity and frequency of these events observed in last years, can be related to climatic changes caused by anthropic actions (IPCC, 2007; Cox et al., 2008). These climatic changes can alter the regimes of precipitation in the Amazon (Sorribas et al., 2016). The increase in ocean temperature, intensified by anthropic actions, can increase the rainy period and hence the occurrence of floods in the Amazon region, as those observed in the last decade (Marengo & Espinoza, 2015; Barichivich et al., 2018). Noticeably, these climatic changes may account for the perceived increase in floods by fishers in the Trombetas River, in the absence of major environmental impacts, such as dams or deforestation.

As recognized by fishers in all studied rivers, droughts and floods can affect fish in Amazonian rivers by influencing fish abundance, biomass and reproduction (Bodmer et al., 2018; Correia et al., 2008). These hydrological changes can ultimately affect the fisheries in the Amazon region, representing a risk for the food security of riverine people (Röpke et al. 2022). Most of the interviewed fishers mentioned negative effects of drought on fish, which would ultimately cause fish population declines, especially in the drier Tocantins River. The river fragmentation and habitat restriction are among the drivers of fish mortality during droughts (Fabré et. al., 2017; Bodmer et. al., 2018), when fish can be trapped in lakes with reduced availability of food and oxygen (Fernandes et. al., 2009; Hurd et. al., 2016). The reduction on food for fish caused by droughts were also mentioned by the interviewed fishers in the three studied rivers. The combination of the aforementioned factors, such as restrictions in habitat, food and oxygen availability, can reduce the abundance and biomass of fish during river droughts (Halls & Welcomme, 2004; Bodmer et al., 2018), which is in agreement with fishers' knowledge. Moreover, fish abundance may be further reduced by an intensified fishing pressure during droughts, when fish became concentrated in a shorter aquatic area (Freitas et al., 2012; Endoa et al., 2016), as mentioned by fishers in all studied rivers.

The interviewed fishers in the three rivers mentioned that floods would have mostly positive effects on fish, manifested through use of the floodplain forest (igapós) by fish. The ecological literature recognizes the importance of these flooded forests during seasonal floods, as flooded forests provide abundant food for fish in the form of fruits, leaves and invertebrates, as well as providing shelter from predators among the submerged roots and vegetation (Goulding, 1980; Correia et. al., 2008; Hurd et. al., 2016). The increased water connectivity during floods facilitates movement and migration of fish species and may trigger the reproduction and spawning in some fish species (Freitas et. al., 2012; Hurd et. al., 2016). Furthermore, these flooded forests may be nursery grounds for fish in its early developmental stages (Sanchéz-Botero & Araújo-Lima, 2001; Lima & Araújo-Lima, 2004). During prolonged floods, fishes may frequent these flooded forests rich in nutrients for longer periods, hence expanding fish reproduction period and leading to more abundant fish stocks (Goulding et. al., 2003; Bodmer et. al., 2018). This increase in fish abundance linked to floods was also mentioned by fishers in the Tapajós and Tocantins rivers. However, extreme floods can cause negative impacts on small-scale agriculture, husbandry of small animals and fisheries, due to loss of terrestrial area and difficult to catch fishes (Coomes et. al., 2010; Tregidgo et. al., 2020). All these effects need to be accounted for, together with fishers' knowledge and perceptions (Guerreiro et al., 2016), to estimate the impacts of extreme floods on the livelihoods of riverine people.

Conclusions

The three distinct datasets analyzed here (mapping, hydrological data and fishers' knowledge) indicate distinct degrees of environmental change in the studied rivers. The maps clearly show a gradient of anthropic changes, from the more pristine and less altered Trombetas river, the moderately altered Tapajós and the more intensely changed landscape in the Tocantins River. These changes are not necessarily reflected in the hydrological data, which showed similar overall hydrological profiles across time in the three rivers. The three datasets analyzed provided comprehensive and complementary information on the current status and environmental changes affecting three major clear water rivers in the Brazilian Amazon. The fishers' knowledge was a useful and unique source of 'on the ground' and detailed data to track some of these long-term changes in water quality and hydrology. This study reinforce the importance of including fishers' knowledge to evaluate ecological changes in poorly studied aquatic ecosystems (Silvano et al. 2023), such as in tropical rivers. The results indicate the need for ecological restoration and protection of remaining natural aquatic ecosystems and forested areas in the more impacted Tocantins River; the need to mitigate current impacts from gold mining in the Tapajós River, and the importance of maintaining the Trombetas (the less altered river basin) and Tapajós River free from dams. The conservation and restoration of these three clear water tropical rivers is paramount to the maintenance of natural hydrological cycles that support the biodiversity, fisheries and people livelihoods.

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Tables

Table 1. The studied fishing communities in the Tapajós, Trombetas and Tocantins rivers showing number of interviewed fishers in each community, community number correspond to community location shown in Fig. 1.

River	Community number (codes)	Community	Number of interviewees
Trombetas	1	Cachoeira Porteira	10
	2	Tapagem	8
	3	Muçurá	4
	4	Varjão	7
Tapajós	5	Pimental	4
	6	São Luiz do Tapajós	3
	7	Canaã	1
	8	Miritituba	8
	9	Pedra Branca	9
	10	Barreiras	12
	11	Brasília Legal	15
	12	Cauaçuepá	13
	13	Cupari	2

Tocantins	14	Vila Taurí	12
	15	Espírito Santo	7
	16	Apinagés	9
	17	Santa Cruz	5

Figures

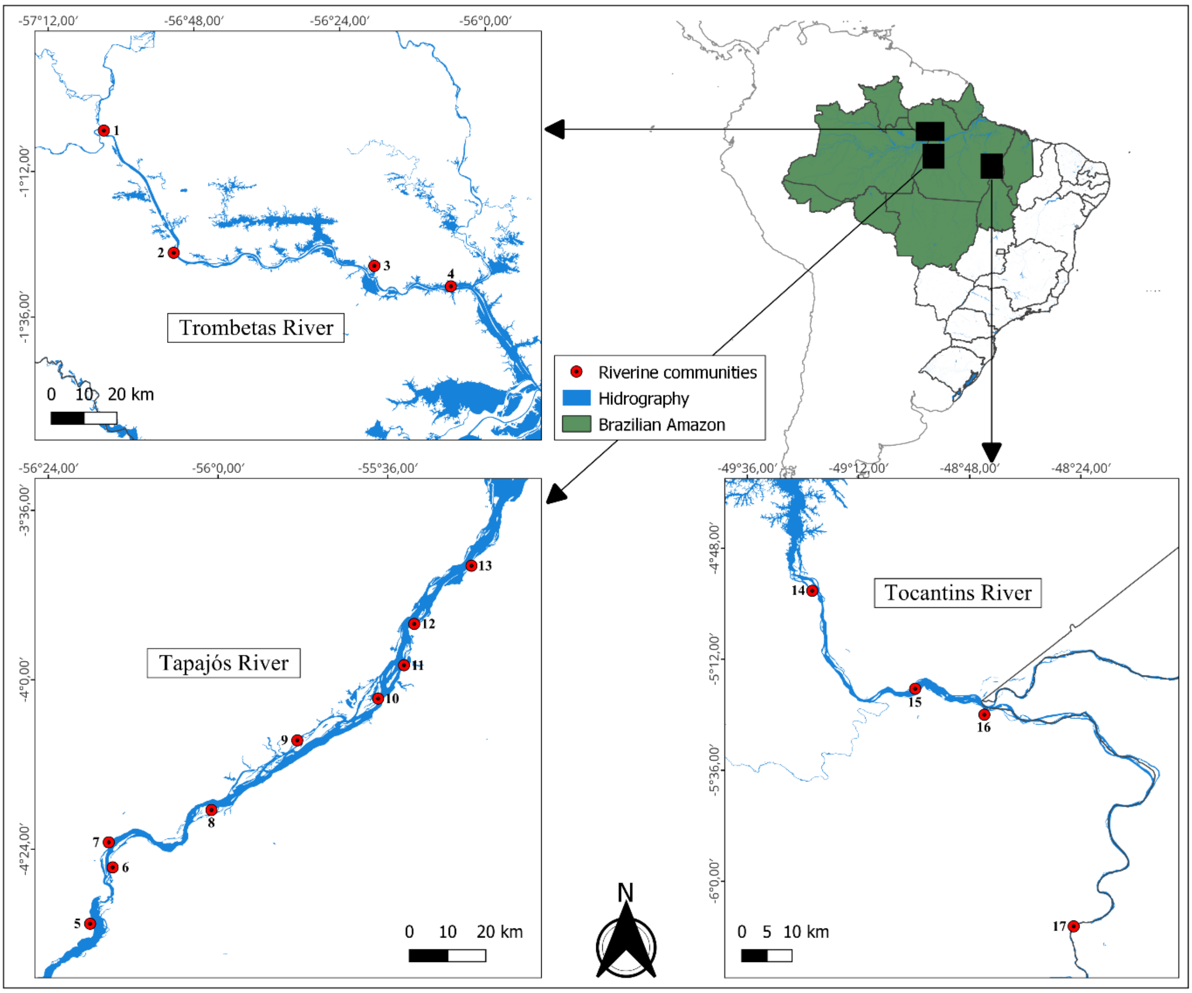
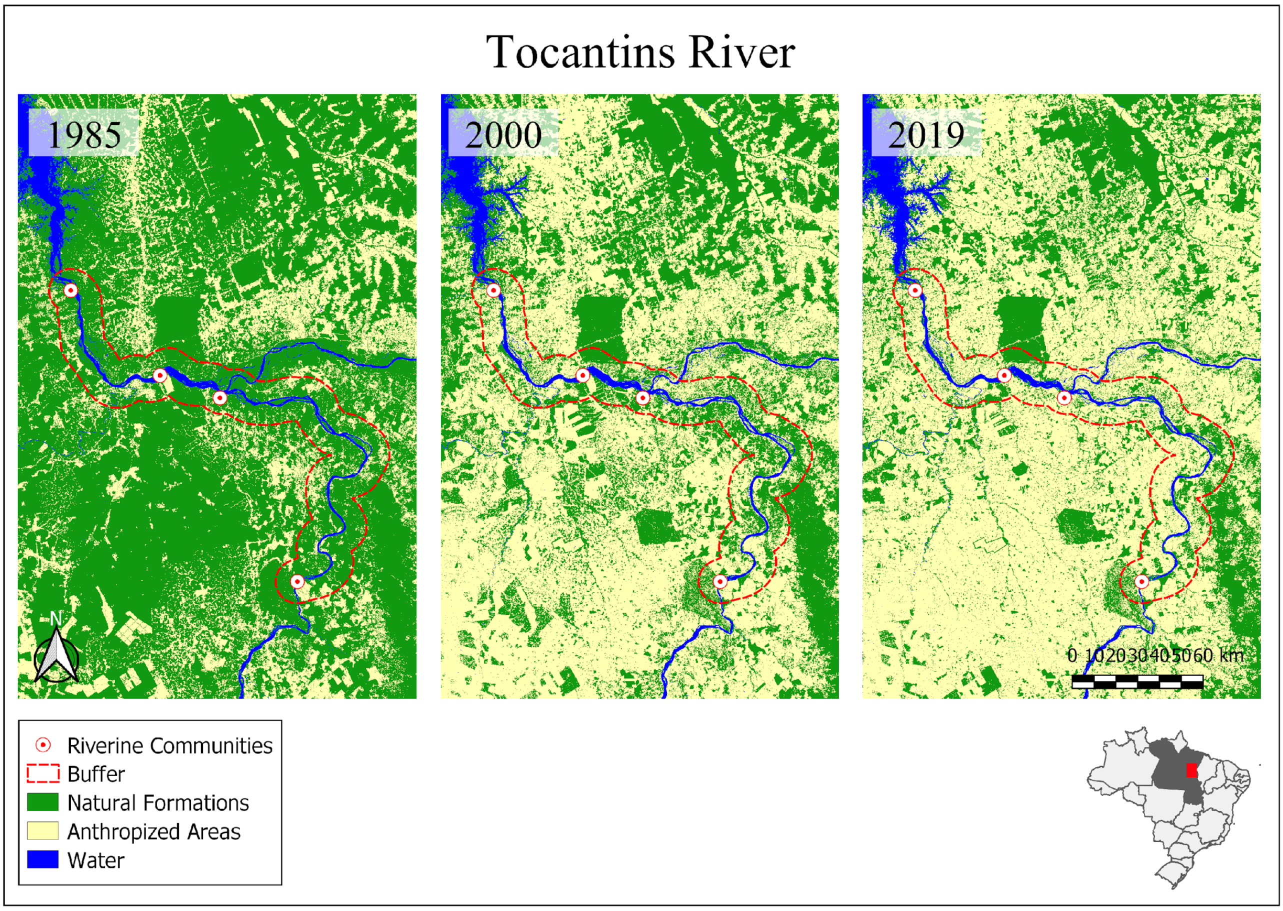
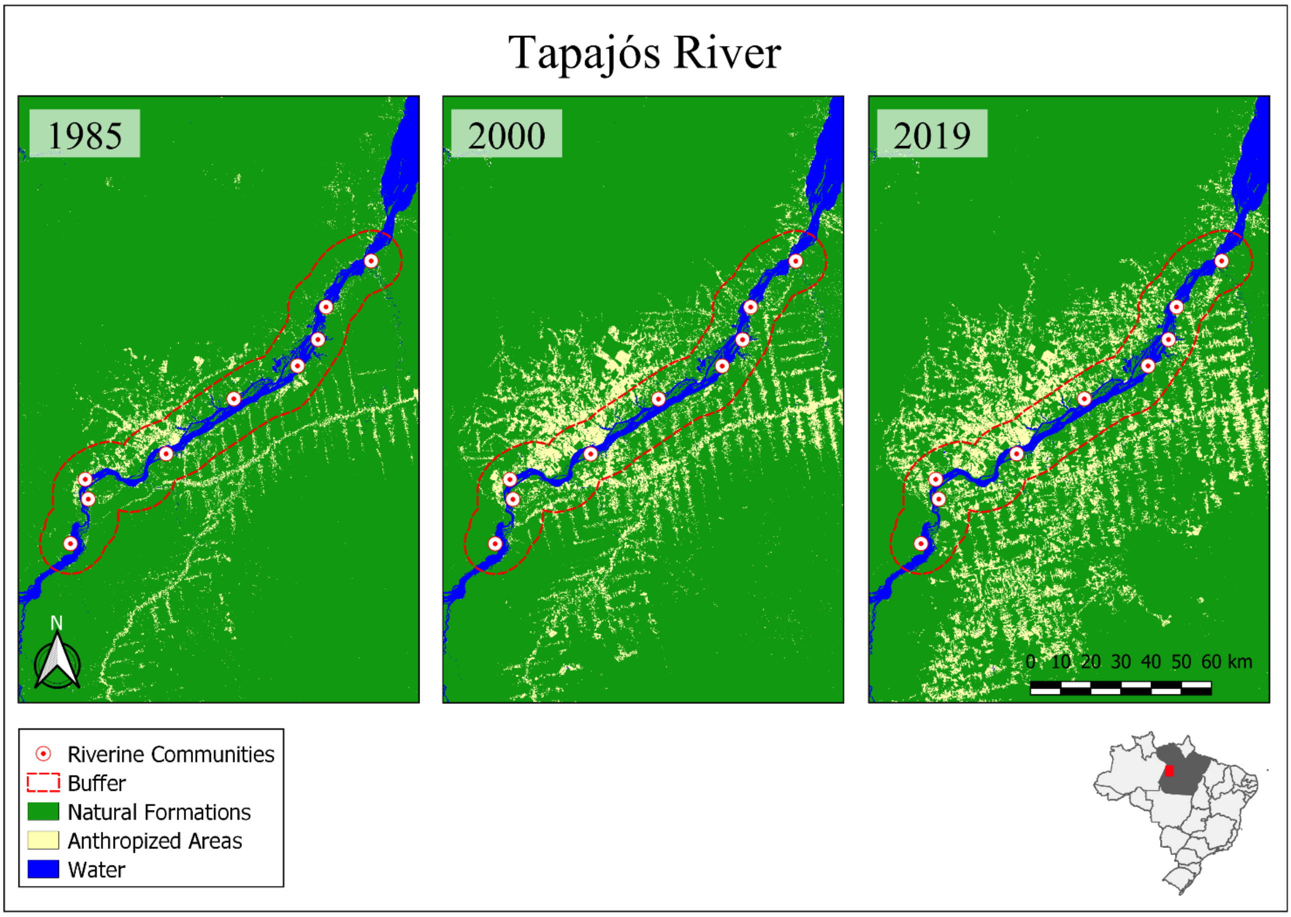


Fig. 1. The three studied rivers in the Brazilian Amazon, showing the studied fishing communities (red dots), names of communities are in Table 1.

a)



b)



Tapajós River
1985
2000
2019
N
0 10 20 30 40 50 60 km
Riverine Communities
Buffer
Natural Formations
Anthropized Areas
Water

c)

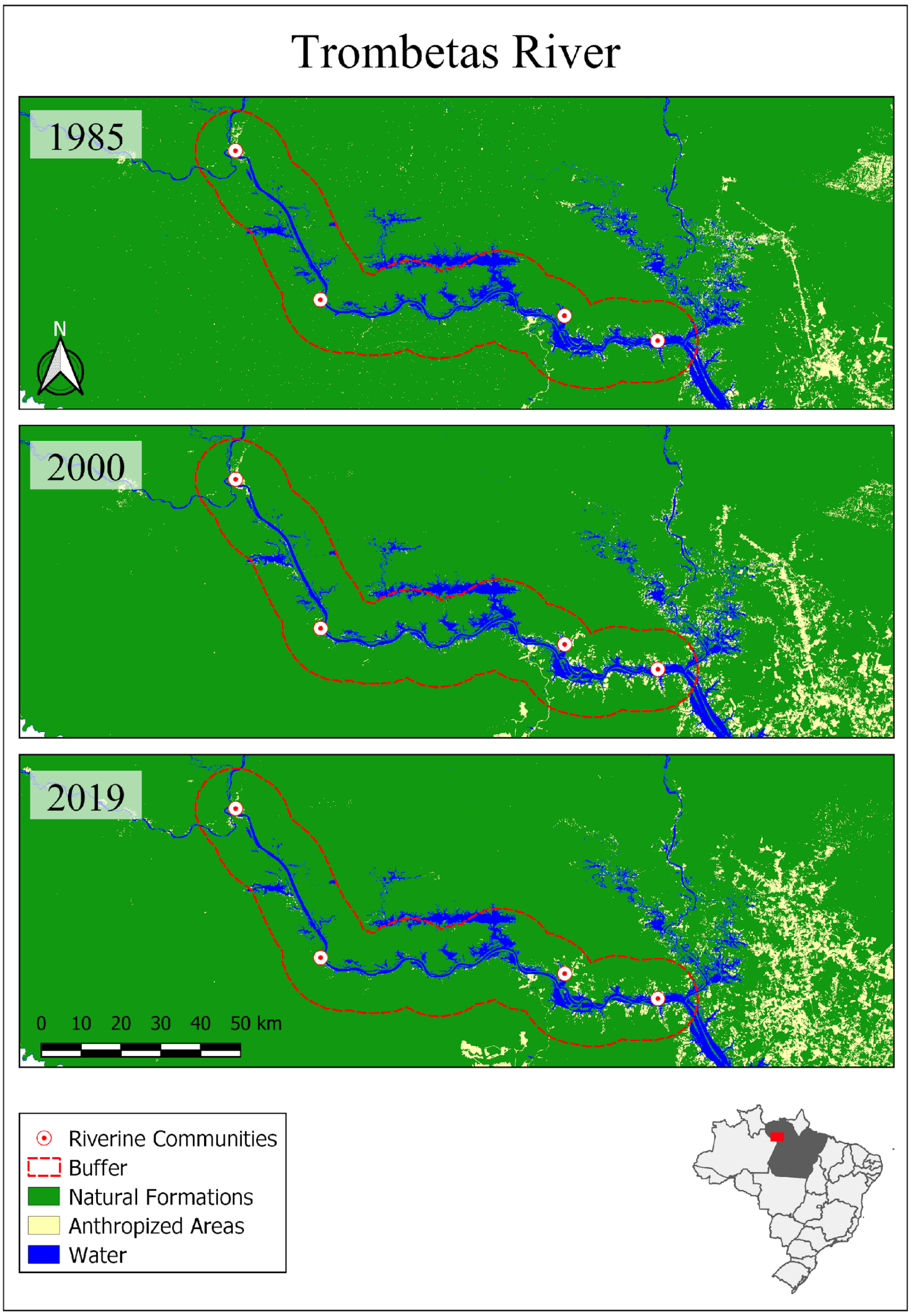
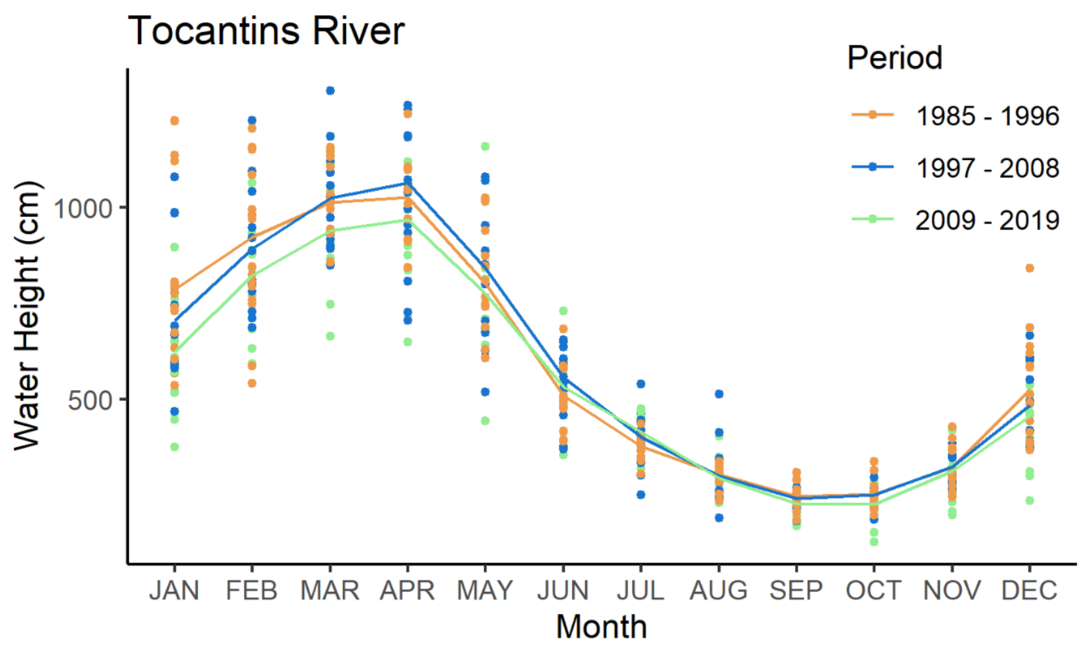


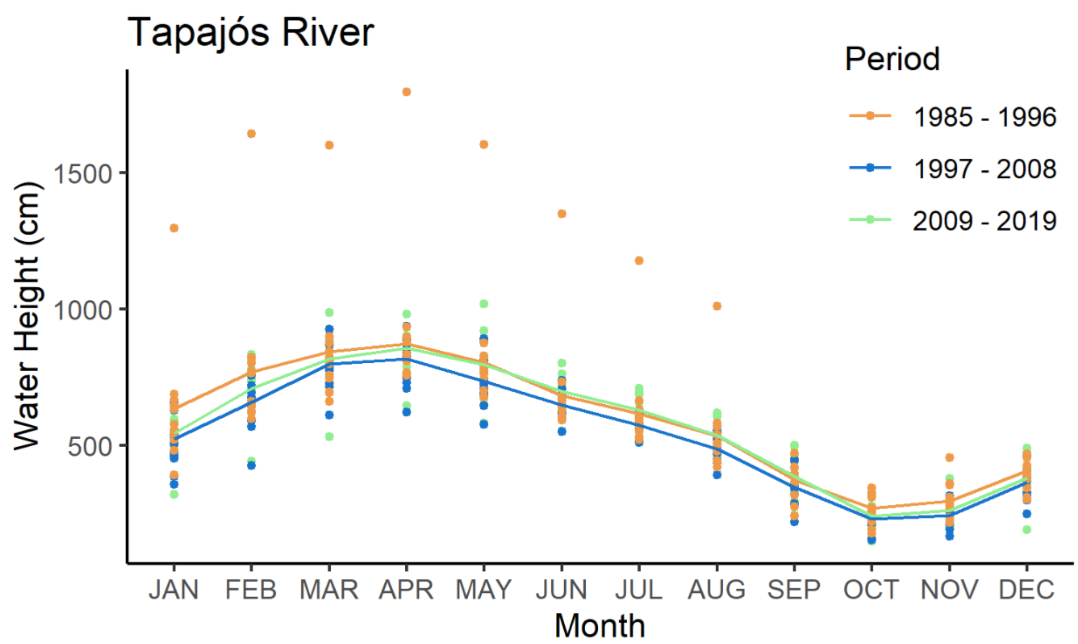
Fig. 2. Landscape cover analysis using data from MapBiomas project for the rivers a) Tocantins, b) Tapajós and c) Trombetas, showing the location of studied communities, buffer

considered for analysis and the landscape categories.

a)



b)



c)

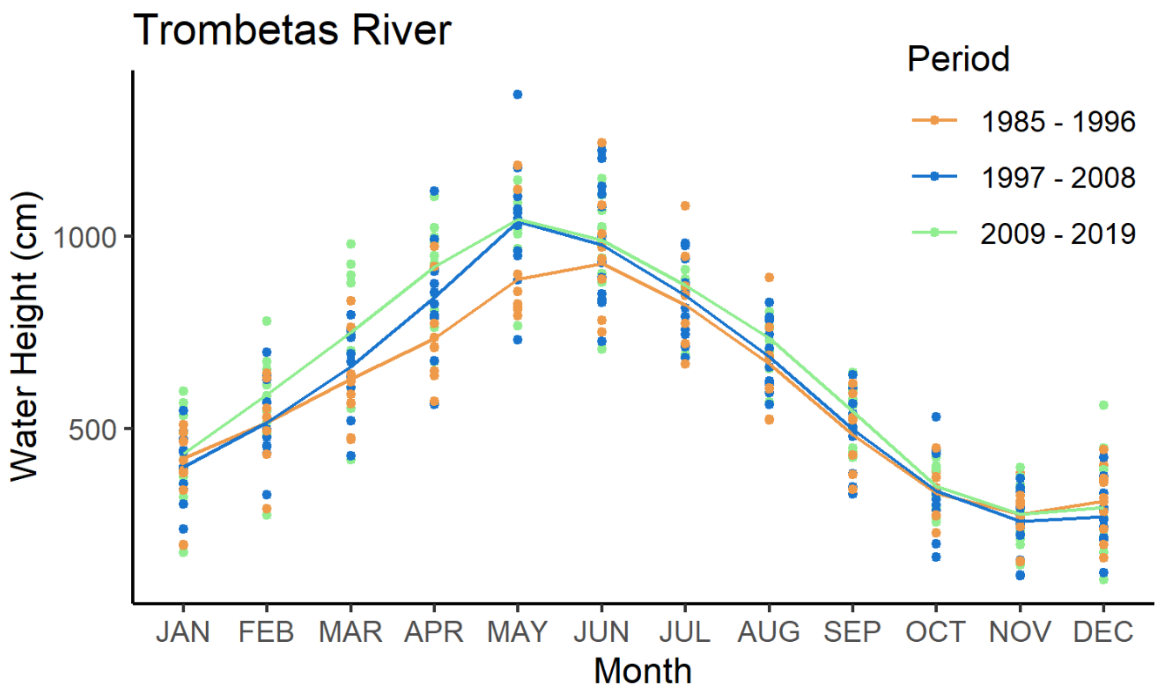


Fig. 3. Monthly means of water level (height in cm) for the rivers a) Tocantins, b) Tapajós and c) Trombetas, during three time periods. Points are monthly means for each year and lines are overall monthly mean for the time period.

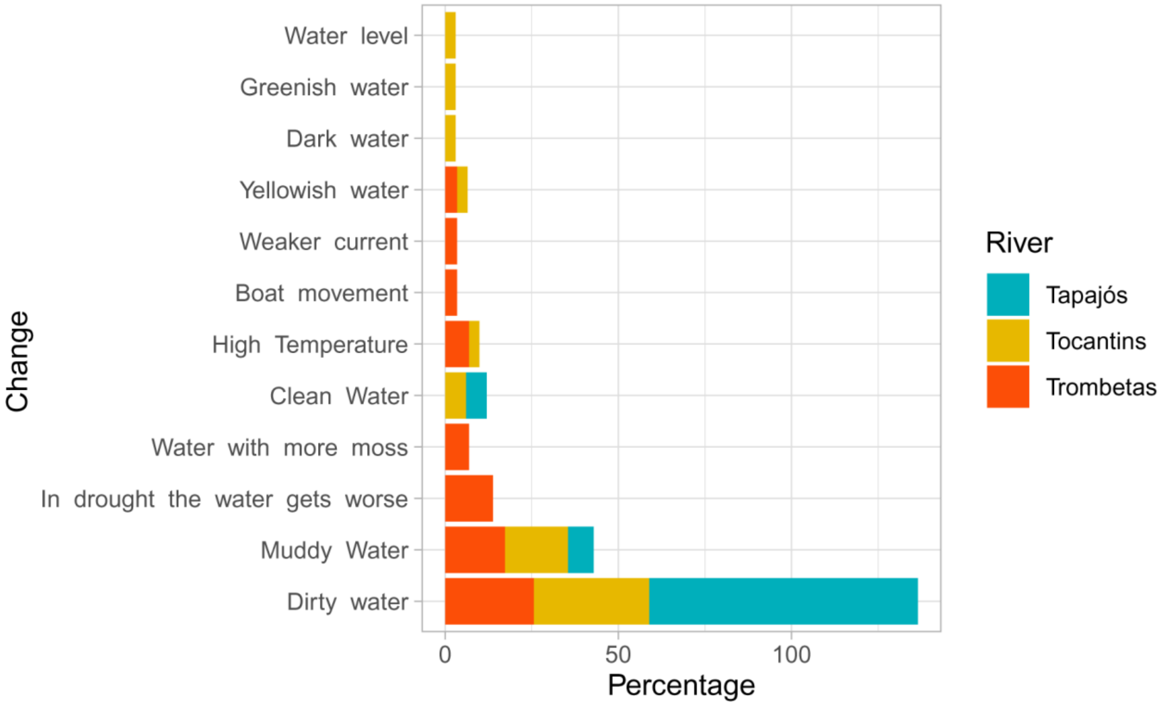


Fig. 4. Changes in water quality mentioned by the interviewed fishers in the Tapajós (n = 67 fishers), Tocantins (n = 33) and Trombetas (n = 29) rivers, since the time the interviewed fishers started their fishing activities. Numbers are percentages of interviewed fishers who mentioned each change in each river (marked by color). Percentages may sum more than 100 %, as the same fisher can cite more than one change.

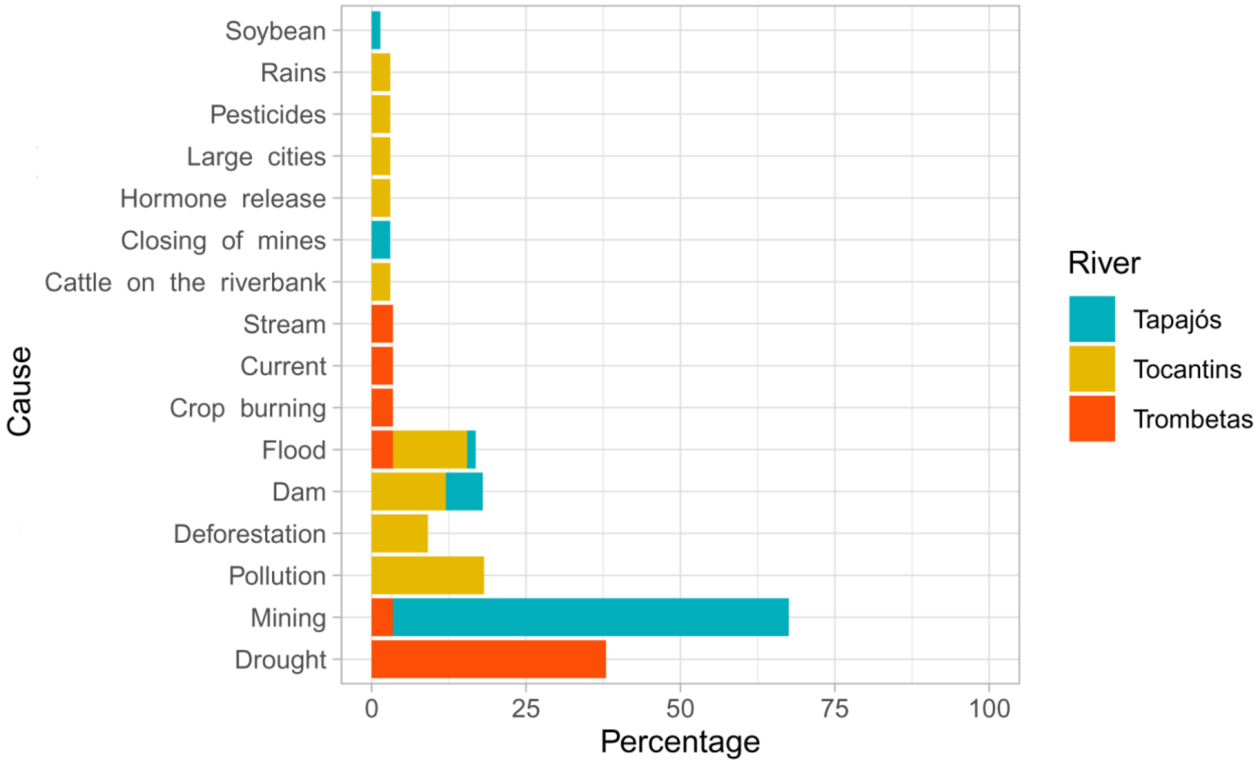


Fig. 5. Possible causes for the reported changes in water quality (see Fig. 4) mentioned by the interviewed fishers in the Tapajós (n = 67 fishers), Tocantins (n = 33) and Trombetas (n = 29) rivers, since the time the interviewed fishers started their fishing activities. Numbers are percentages of interviewed fishers who mentioned each change in each river (marked by color). Percentages may sum more than 100 %, as the same fisher can cite more than one change.

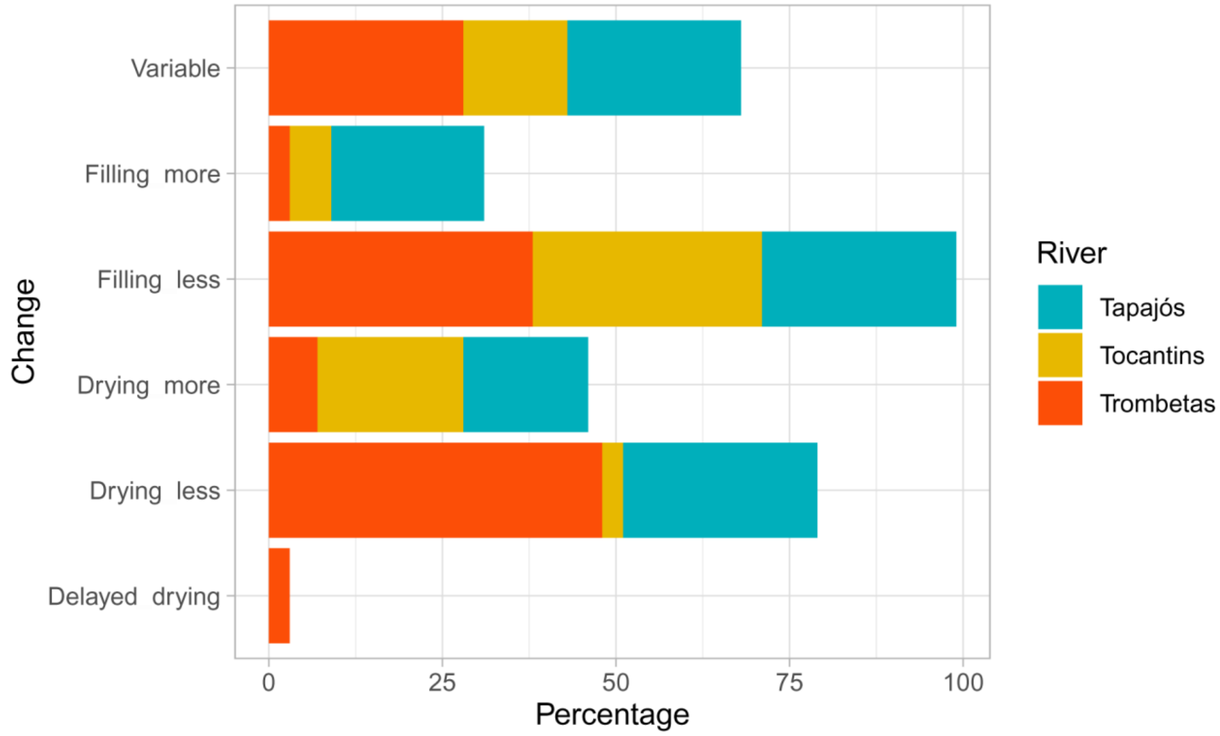


Fig. 6. Changes in hydrology (floods and droughts) mentioned by the interviewed fishers in the Tapajós (n = 67 fishers), Tocantins (n = 33) and Trombetas (n = 29) rivers, since the time the interviewed fishers started their fishing activities. Numbers are percentages of interviewed fishers who mentioned each change in each river (marked by color). Percentages may sum more than 100 %, as the same fisher can cite more than one change.

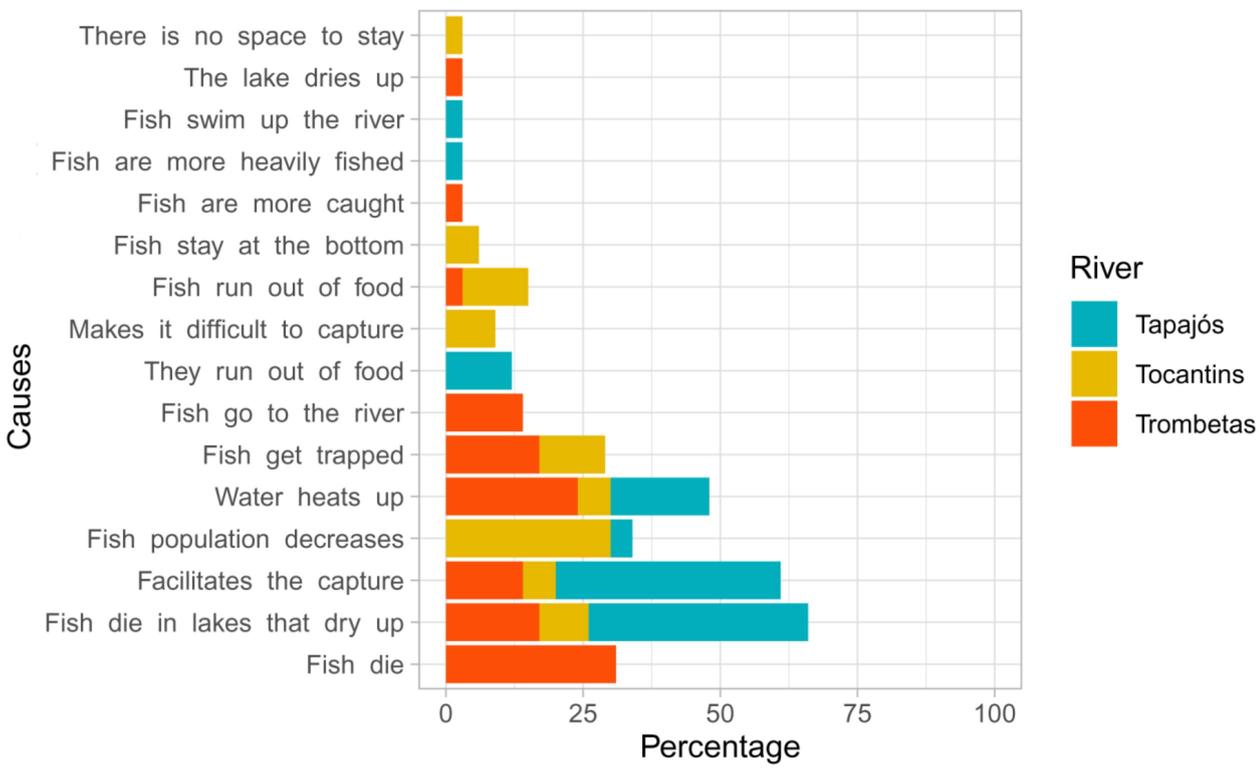


Fig. 7. Effects caused by droughts on fish according to the interviewed fishers in the Tapajós (n = 67 fishers), Tocantins (n = 33) and Trombetas (n = 29) rivers. Numbers are percentages of interviewed fishers who mentioned each change in each river (marked by color). Percentages may sum more than 100 %, as the same fisher can cite more than one change.

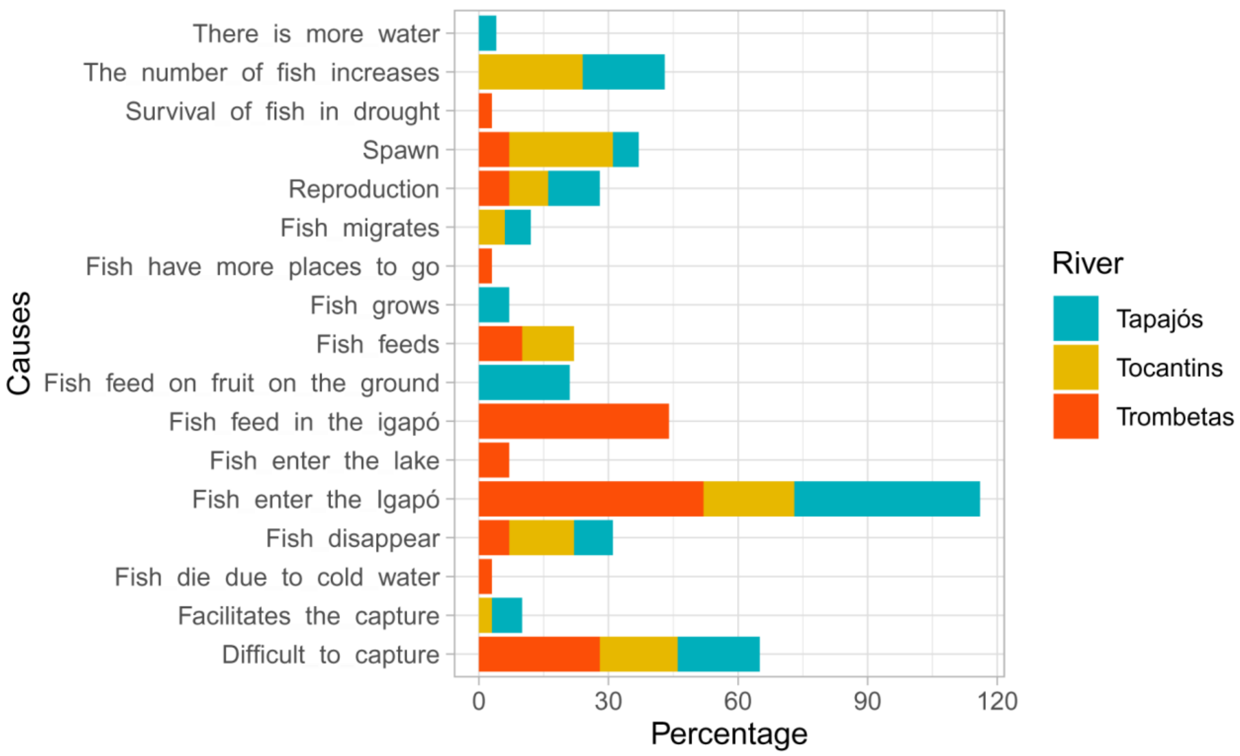


Fig. 8. Effects caused by floods on fish according to the interviewed fishers in the Tapajós (n = 67 fishers), Tocantins (n = 33) and Trombetas (n = 29) rivers. Numbers are percentages of interviewed fishers who mentioned each change in each river (marked by color). Percentages may sum more than 100 %, as the same fisher can cite more than one change.

Supplemental Material

Appendix 1. Questions from the standard questionnaire analyzed in this study. These same questions were asked for all interviewed fishers in all the three studied rivers.

Name: Age: Community: Date:__/__/__

Gender: ( ) Male ( ) Female Fishing experience: How long live in the region?

1) Have you noticed any changes in droughts/floods since you started fishing as a full-time activity? Which changes? Why these occurred?
2) Does the droughts affect fish? How?
3) Does the floods affect fish? How?
4) Have you noticed any changes in water quality since you started fishing as a full- time activity? Which changes? Why these occurred?

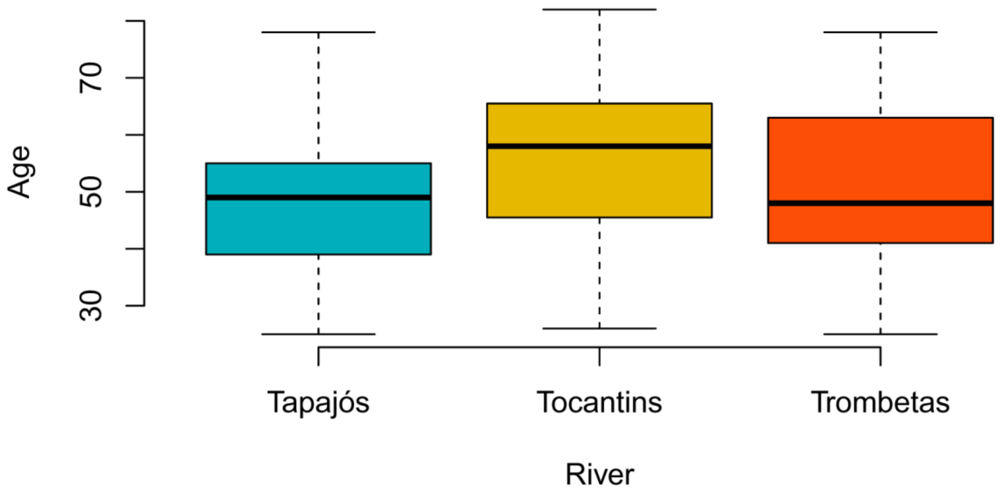


Fig.S1. Mean ages of interviewed fishers in the three studied rivers in the Brazilian Amazon.

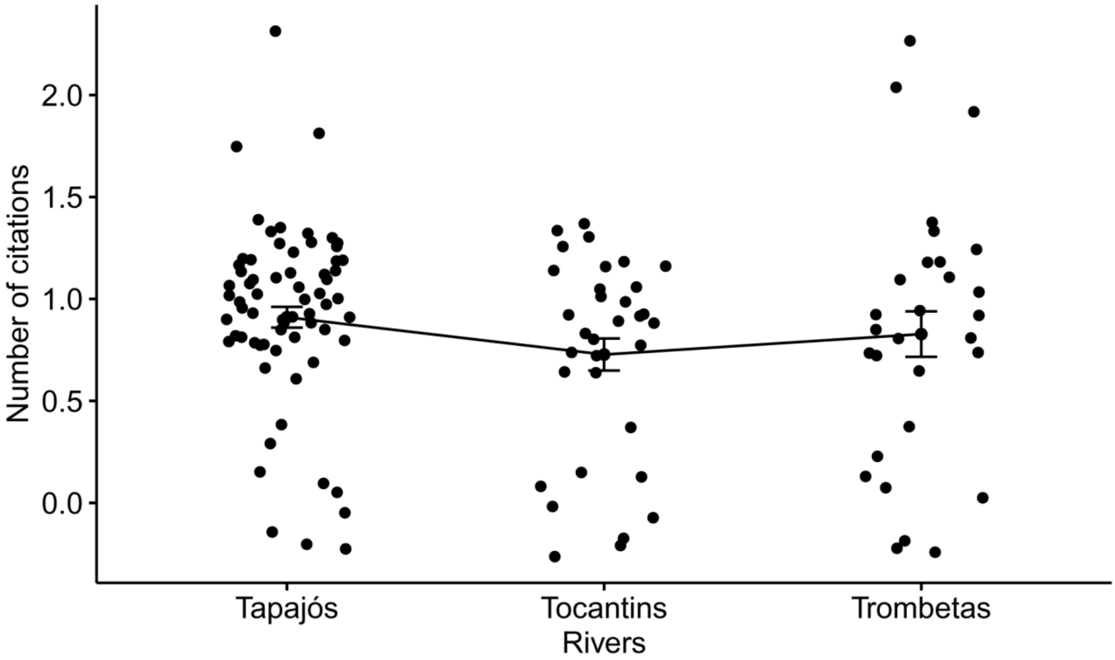


Fig. S2. Comparison of the mean number of citations (dots connected by lines) about changes in water quality (Fig. 4) mentioned by each interviewed fisher (dots) in the Tapajós (n = 67 fishers), Tocantins (n = 33) and Trombetas (n = 29) rivers.

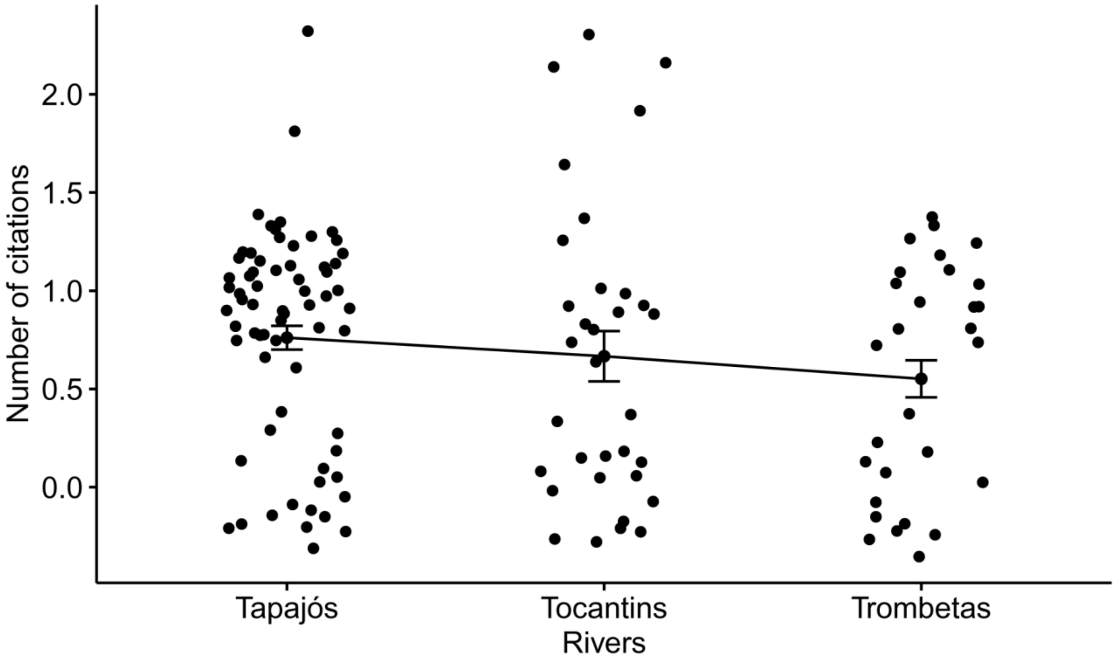


Fig. S3. Comparison of the mean number of citations (dots connected by lines) about causes of changes in water quality (Fig. 5) mentioned by each interviewed fisher (dots) in the Tapajós (n = 67 fishers), Tocantins (n = 33) and Trombetas (n = 29) rivers.

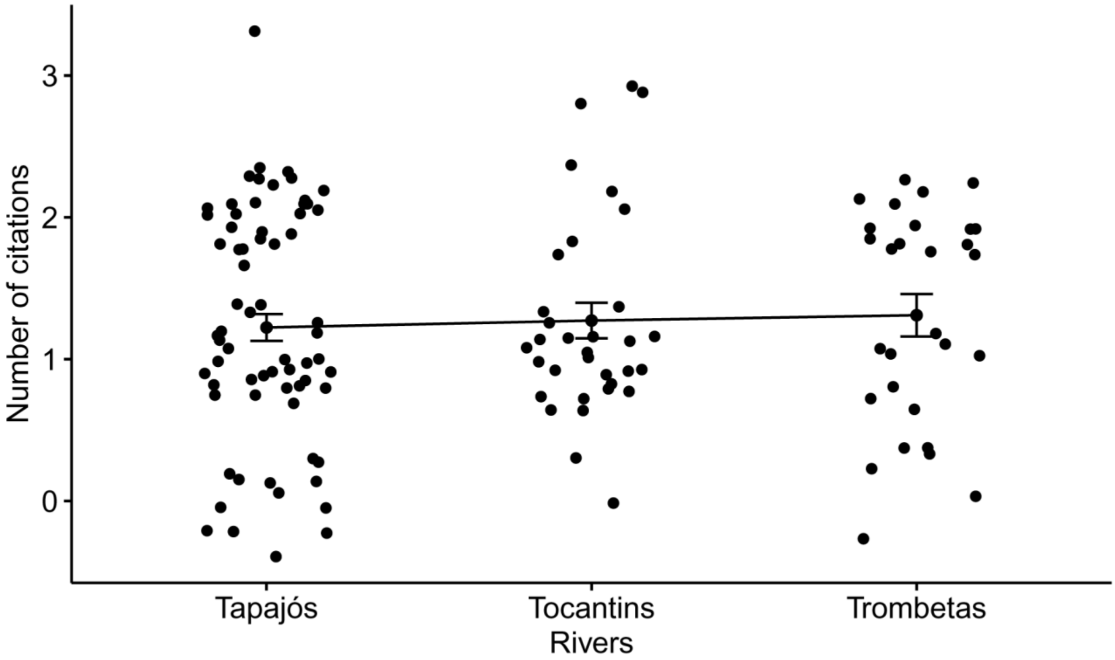


Fig. S4. Comparison of the mean number of citations (dots connected by lines) about changes in hydrological regime (Fig. 6) mentioned by each interviewed fisher (dots) in the Tapajós (n = 67 fishers), Tocantins (n = 33) and Trombetas (n = 29) rivers.