Ingestion of fish is considered the main pathway of human exposure to methylmercury (MeHg), particularly for riverside populations, where fish is the main source of protein. The objective of this study was to estimate concentration of MeHg based on total concentration of mercury in muscles of three species of carnivorous fish: Boulengerella cuvieri (bicuda), Serrasalmus rhombeus (piranha), and Hydrolycus armatus (cachorra), collected from Teles Pires River, Brazil. Furthermore, we calculated human health risk related to MeHg contamination caused by fish consumption. Fish were collected in 20 field campaigns from December 2011 to September 2016 at Teles Pires River, in area of influence of Colider hydroelectric plant. Risk index (RI) related to ingestion of MeHg through fish intake was calculated considering that MeHg corresponds to around 90% of mercury in fish. There were no significant differences in average mercury concentration between all species: S. rhombeus (0.304 mg/kg$^{-1}$), H. armatus (0.229 mg/kg$^{-1}$), and B. cuvieri (0.199 mg/kg$^{-1}$). RI calculated for sensitive groups (lactating women, breastfeeding infants and children) and RI calculated for general population presented average values, suggesting adverse health effects. This first assessment on MeHg and human exposure to people from Teles Pires River area through fish consumption suggests that mercury concentrations might be posing health adverse effects on people of this sensitive group. Further studies involving more fish specimens and considering fish biological factors are needed to fully understand health risks of mercury exposure to humans in this region.

Keywords: Fish consumption, Carnivores, Risk index, Human health, Tapajos basin

1. Introduction

Mercury (Hg) is a naturally occurring element in earth's crust released by erosion prone rocks and geological movements and is redistributed between and within ecosystems by vegetation and soil or water movements (Sundseth et al., 2017). Anthropogenic mercury sources are mainly comprised of artisanal gold mining, fossil fuel powered power plants, ferrous and nonferrous metal industries, caustic soda manufacturing, waste incinerators, and cement factories (Pirrone et al., 2010). Mercury is also found in agricultural inputs used extensively in agriculture throughout year (Wuana and Okieimen, 2011; Opaluwa et al., 2012; Anim-Gyampo et al., 2013).

In the southern Amazon region, the main anthropogenic sources of mercury are gold mining, agriculture related land use activities, and forest burning (Matos et al., 2018). This area endured intense gold mining activity between 1970s and 1990s, followed by a decline due to reduced gold deposits in the region (Lobo et al., 2016). Logging, agriculture, and cattle ranching, all activities which use fire as a process to create open land, also contribute to erosion of naturally mercury enriched Amazonian soils (Lechler et al., 2000; Cordeiro et al., 2002). Land use activities in the Amazon were significantly accelerated in 1970, when manual workers, colonists, and landowners from the south and southeast regions of Brazil colonized drainage basins (Picoli, 2004). This colonization resulted
in increased mercury runoff into rivers as seen in sediments of the Tapajós River (Roulet et al., 2000).

The most recent anthropogenic activity to contribute to mercury release in Amazonian environment is construction of hydropower dams, justified on basis that they supply energy needed for economic development (Latrubesse et al., 2017). In Teles Pires River, for example, four hydropower plants (HEPs) were recently installed along a 450 km of river extension (Matos et al., 2020). HEP reservoirs, backwater areas, marginal and flood lakes are of concern as regards mercury exposure to wildlife and humans as they present biogeochemical conditions that favor mercury methylation (Lacerda and Malm, 2008). This is because mercury methylation is favored in aquatic environments in Amazonian hydro dams, typically presenting anoxic, suboxic, and slightly acidy waters with high concentrations of dissolved organic matter and intense microbiological activity (Lacerda and Malm, 2008).

Among mercury forms that are present in aquatic environments, methyl mercury (MeHg) incites greatest interest from an ecotoxicological perspective, since it is a neurotoxin and has a tendency to bioaccumulate and biomagnify in trophic chains (Bisiniotis and Jardim, 2004). Fish intake is considered the main pathway to human exposure from MeHg, particularly for riverside populations as fish is their main source of protein (Milhomem-Filho et al., 2016). To this end, analysis of fish muscle is a powerful tool to determine risk of mercury transfer to humans who feed on fish. Furthermore, information on MeHg concentrations in fish enables us to assess health risks posed to humans through fish intake (Copat et al., 2012).

In aquatic ecosystems, elemental (Hg⁰) and inorganic (Hg²⁺) forms of mercury are predominant (Verhaert et al., 2019). However, mercury contained in rivers can become more dangerous due to possibility of methylation (MeHg) with action of methanogenic bacteria (Shao et al., 2012). Because MeHg is soluble in fat and well absorbed by biological membranes and digestive tracts of aquatic organisms (Lacerda and Malm, 2008), it is readily absorbed by aquatic biota, bioaccumulating and biomagnifying into aquatic food chains (Porcela, 1994).

Mercury bioaccumulation can vary across ichthyofauna living in same water body, and such differences might be related to life cycle and feeding habits of each species (Hosseini et al., 2013). Organisms at the top of food chain usually present higher mercury concentrations than those at lower trophic levels, even when they inhabit same aquatic system (Campbell, 1994; Kidwell et al., 1995; Voigt, 2004; Terra et al., 2008). According to World Health Organization (WHO, 2006), recommended safety limit for fish consumption is 0.5 mg/kg of mercury. However, in Brazilian Amazon, studies have shown several fish species (carnivores, omnivores, planktivores, and piscivores) above this threshold limit (Kasper et al., 2012; Bastos et al., 2015; Castro et al., 2016; Lino et al., 2018). In Manuel Hydroelectric reservoir on Jamari River, carnivorous fish species presented high levels of mercury concentration upstream (0.545 mg/kg) and downstream of reservoir (1.366 mg/kg; Kasper et al., 2012). In a stretch of river close to Rio Madeira Hydroelectric Complex, mercury concentrations ranged from 0.51 to 1.242 mg/kg (Bastos et al., 2015).

In view of this, studies in the Amazon region are necessary to understand whether the consumption of these fish collected in these hydro dam areas in the Amazon may represent a risk to the health of riverside communities and indigenous populations.

Considering the dramatic increase in hydro dam constructions in the Amazon region in the last 20 years and the natural high levels of mercury in the soils, the objective of this study was to establish a background concentration for carnivorous fish species prior to the flooding of Colider Hydro Dam so that future studies after flooding can be compared against. We calculate the concentration of MeHg, based on the total concentration of mercury (THg) in the muscle of different species of carnivorous fish: Boulengerella cuvieri (bicuda), Serrasalmus rhombus (piranha), and Hydrolagus armatus (cachorra), collected from Teles Pires River. Specifically, we tested the hypothesis that fish species have same THg and MeHg concentrations in their muscle mass. The human health risk associated with MeHg consumption through fish was calculated for different populations in Mato Grosso, so as to assess the health risk consumption that these fish may represent for traditional communities consuming them.

2. Materials and methods

2.1. Study area

Site of this study is Teles Pires River, between municipalities of Colider and Itaíba in Mato Grosso [Figure 1]. Fish were collected from Teles Pires River (Mato Grosso), one of the main tributaries of Tapajós River of Brazilian Amazon. A range of land use is known in this region: cattle ranching, agriculture, gold mining, dumping of tannery effluents, and currently, hydropower plants are all present in area (Matos et al., 2018). These land use processes make this area highly prone to mercury runoff from soil and consequent deposition into water bodies (Roulet et al., 2000). Furthermore, artisanal gold mining activities using mercury for gold amalgamation processes directly discharged mercury into rivers (Malm et al., 1997). The construction of the Colider Hydroelectric Plant started in 2011, with the formation of the reservoir at the end of 2017 (Matos et al., 2020); the capture of the specimens of this study was before the formation of the reservoir.

2.2. Fish collection and biometrics

Fish were collected in 20 fieldwork campaigns between December 2011 and September 2016. Considering that predatory top-of-the-chain species provide an integrated view of water body (Flotemersch et al., 2006) and are good models for mercury analysis, we analyzed three species of carnivorous fish: B. cuvieri (bicuda), S. rhombus (piranha), and H. armatus (cachorra; Table 1). Trawls, fixed nets, cast nets, and reel rods were used to capture fish. After capture, fish were euthanized with Eugenol®, following guidelines established by animal ethics council (American Veterinary Medical Association, 2001). Fish samples were packed in Ziploc bags and stored in portable cooler with ice and immediately transported to Laboratório de
Ictiologia da Amazônia Meridional-LIAM at Universidade do Estado de Mato Grosso-UNEMAT. Weight (g), total length (cm), and standard length (cm) for each fish sample were measured and recorded.

Muscle sample (approximately 2 cm$^3$) was collected from dorsolateral part of fish, from above lateral lines, using stainless steel chirurgical instruments. These tissues were stored at 2°C until mercury analyses. Voucher specimens were deposited in collection at laboratory LIAM at UNEMAT University Campus Alta Floresta.

2.3. Mercury analysis

Mercury analyses were performed in Laboratório de Ecotoxicologia, Centro de Pesquisa em Limnologia, Biodiversidade e Etnobiologia—CELBE, UNEMAT, Campus de Cáceres. Fish digestion was conducted following method described in Bastos et al. (1998). Approximately 0.5 g (dry or wet weight) of fish muscle and replica were weighted in glass tubes. One milliliter of H$_2$O$_2$ (Merck) and 4 ml of H$_2$SO$_4$:HNO$_3$ (1:1 v/v) solution were added and glass tubes were placed in water bath at 60°C for approximately 30 min. When samples cooled down, 5 ml of KMnO$_4$ 5% solution was added (m/v) to mixture digest and tubes were returned to water bath at 60°C for 30 min. Once cooled, glass tubes with digestes were covered with plastic film and left to rest for approximately 12 h.

After 12 h, 1 ml of hydroxylamine was added to digest solution to neutralize oxidizing medium. Final digest volume was set at 13 ml using Milli-Q water. Mercury analyses were performed using an Atomic Absorption Spectrometer with a flow injection system (FIMS—400; Perkin Elmer). Standard reference material DORM-3 from National

Table 1. Predatory fish species collected from Teles Pires River. DOI: https://doi.org/10.1525/elementa.2021.020.t1

| Common Name | Scientific Name              | Family       | Diet         | Reproductive Season | Source                          |
|-------------|-------------------------------|--------------|--------------|---------------------|---------------------------------|
| Peixe-cachorra | *Hydrolycus armatus*         | Cynodontidae | Carnivorous  | Flood (migratory)   | Goulding (1980)                 |
|             | (Jardine and Schomburgk, 1841)|              |              |                     |                                 |
| Bicuda      | *Boulengerella cuvieri*       | Ctenoluciidae| Carnivorous  | Flood (migratory)   | Santos et al. (2004) and Pereira et al. (2012) |
|             | (Agassiz, 1829)               |              |              |                     |                                 |
| Piranha     | *Serrasalmus rhombeus*        | Serrasalmidae| Carnivorous  | Flood (sedentary)   | Santos et al. (2006)            |
|             | (Linnaeus 1766)               |              |              |                     |                                 |

Figure 1. A. Map of Brazil. B. Map of State of Mato Grosso, highlighting Teles Pires River. C. Study Area, with indications to our sampling areas (black dots), between municipalities of Itaúba (11°14'6,36"S e 55°27'6,3"O) and Colíder (10°59'4,49"S e 55°49'25,51"O). DOI: https://doi.org/10.1525/elementa.2021.020.f1
Institute of Standards and Technology (NIST) was analyzed for every 20 samples to discover quality assurance and quality control. NIST DORM-3 certified THg concentration as 0.382 ± 0.060 mg/kg. Analyses in our lab were recorded as 0.416 mg/kg and 0.352 mg/kg. Replicas had a variation coefficient of less than 15%.

2.4. Estimating human health risk

Human health risk assessment was carried out in accordance with U.S. Environmental Protection Agency (USEPA, 2000). We considered four different consumption rates of B. cuvieri, S. rhombeus, and H. armatus (Table 2).

In this study, MeHg concentrations were estimated based on previous studies demonstrating that approximately 90% of THg concentration in fish muscle is present as MeHg (Bloom, 1992; Akagi et al., 1995; Malm et al., 1995; Micaroni et al., 2000; Kehrig et al., 2008). MeHg exposure levels to humans resulting from intake of fish muscle (tissue that is usually consumed) were calculated following MeHg mean daily intake (MDI) equation (FAO, 2006; WHO, 2006, 2008):

$$\text{MDI} (\text{mg/kg/day}) = \frac{(C \times IR \times FE \times ED)}{(BW \times AL)}$$

Where:

- $C =$ MeHg concentration in fish muscle (mg/kg), minimum and maximum MeHg concentrations were used for each fish species to calculate amplitude,
- $IR =$ Average intake rate (Table 2),
- $FE =$ Frequency of exposure (365 days/year),
- $ED =$ Lifetime exposure duration (considered here as 70 years),
- $BW =$ Individual body weight (considered here as 70 kg),
- $AL =$ Average lifetime (considered here as 70 years × 365 days/year).

Risk assessment deleterious health effects were calculated using risk index (RI), expressed as ratio between MDI and THg oral reference dose (RfD). Note our calculations considered people to be 70 years of age, as a conservative mercury lifetime exposure. RI provides magnitude of human population’s exposure in relation to recommended dose. RI was calculated according to the following equation:

$$\text{RI} = \frac{\text{MDI}}{\text{RfD}}$$

Where:

- $\text{MDI} =$ mean daily intake (Calculated in previous paragraph)
- $\text{RfD} =$ MeHg oral intake reference dose (mg/kg/day) established by WHO (2006, 2008) based on highest MeHg intake level recommended as acceptable for an adult human with a body weight of 70 kg. Values for MeHg oral RfD from Food and Agriculture Organization of United Nations were applied in this study (FAO, 2006), as were those from WHO (2006, 2008).

In this study, two RfD values (WHO, 2006) were used to calculate IR:

- $\text{RfD} (\text{table 3}) = 0.0003 \text{ mg/kg/d for general population; }$
- $\text{RfD} (\text{table 4}) = 0.0001 \text{ mg/kg/d for sensitive groups (lactating mothers, infants and children).}$
in the present study is likely a result of differences in the feeding behavior of these three predatory species. A study on biomagnification of mercury in trophic structure of ichthyofauna in Amazon basin suggests that top chain species may be associated with several trophic webs within an ecosystem (Azevedo-Silva et al., 2017). Piranhas are fish with a tooth structure adapted to pull pieces (scales, fins, muscle) from their prey (Piorski et al., 2005), allowing them to feed on larger fish. Although not significantly different, the slightly higher mercury concentrations in Amazonian fish (Pouilly et al., 2012), studies on diet of these species explain increase in mercury concentrations over life of an organism, may not be the main factor that explains increase in mercury concentrations in Amazonian fish (Pouilly et al., 2012), studies on diet of these species show that in Teles Pires River basin these species are piscivorous predators of small caracids (Dary et al., 2017). In this study, average mercury concentrations were B. cuvieri (0.199 mg/kg), followed by H. armatus (0.229 mg/kg) and S. rhombeus (0.304 mg/kg; Table 3). In this study, we analyzed three species from top-of-the-chain fish, and generally these species have higher concentrations of mercury than those of lower trophic levels (Voigt, 2004; Terra et al., 2008). Thus, differences in mercury accumulation found in these fish species in this study may be related to morphological differences, life cycle, and food items of each species (Goulding, 1980; Terra et al., 2008). Because bioaccumulation, defined as increase in mercury concentrations over life of an organism, may not be the main factor that explains increase in mercury concentrations in Amazonian fish (Pouilly et al., 2012), studies on diet of these species show that in Teles Pires River basin these species are piscivorous predators of small caracids (Dary et al., 2017).

4. Discussion
4.1. Total mercury in fish from Teles Pires River
In this study, average mercury concentrations were B. cuvieri (0.199 mg/kg), followed by H. armatus (0.229 mg/kg) and S. rhombeus (0.304 mg/kg; Table 3). In this study, we analyzed three species from top-of-the-chain fish, and generally these species have higher concentrations of mercury than those of lower trophic levels (Voigt, 2004; Terra et al., 2008). Thus, differences in mercury accumulation found in these fish species in this study may be related to morphological differences, life cycle, and food items of each species (Goulding, 1980; Terra et al., 2008). Because bioaccumulation, defined as increase in mercury concentrations over life of an organism, may not be the main factor that explains increase in mercury concentrations in Amazonian fish (Pouilly et al., 2012), studies on diet of these species show that in Teles Pires River basin these species are piscivorous predators of small caracids (Dary et al., 2017). However, a more detailed study in Xingu River showed that for B. cuvieri, the most important food items are Geophagus sp. and Leporinus sp, and for H. armatus, they are Cichla melanica (Barbosa et al., 2018). Piranhas are fish with a tooth structure adapted to pull pieces (scales, fins, muscle) from their prey (Piorski et al., 2005), allowing them to feed on larger fish. Although not significantly different, the slightly higher mercury concentrations found in S. rhombeus in the present study is likely a result of differences in the feeding behavior of these three predatory species. A study on biomagnification of mercury in trophic structure of ichthyofauna in Amazon basin suggests that top chain species may be associated with several trophic webs within an ecosystem (Azevedo-Silva et al., 2017). Species B. cuvieri would be feeding on small non-carnivorous fish, H. armatus would be feeding on small carnivorous fish, and S. rhombeus feeding on large fish that have higher levels of mercury due to bioaccumulation. However, these differences in mercury concentration
in fish of same trophic level are difficult to explain, as there are many factors that may have influenced, or perhaps it would be, synergistic effect of all these factors, requiring further studies on this.

However, one main difference between species analyzed in present study can be migratory fish and sedentary fish. Fish from lentic systems have mercury contents about four times higher than fish from same trophic level in lotic systems, with same concentration of MeHg in water (USEPA, 2010). In the present study, sedentary species *S. rhombus* (piranha) showed higher concentrations of mercury than migratory *H. armatus* and *B. cuvieri*. Piranhas’ preference for lentic environments is already well known (Agostinho and Julio, 2002). Species *H. armatus* and *B. cuvieri* are fish from lotic environments, as they perform long annual reproductive migrations (Agostinho and Julio, 2002). They are likely well-known (Agostinho and Julio, 2002). Species *H. armatus* and *B. cuvieri* are fish from lotic environments, as they perform long annual reproductive migrations (Agostinho and Julio, 2002).

Mercury concentrations in fish from Tapajós basin (in which Teles Pires River is part of) vary between studies, most likely as a result of collection site relating to anthropogenic activities, including gold-digging, deforestation, and agriculture (Table 6). For *B. cuvieri*, on Teles Pires River in a preserved area (Castilhos et al., 2012), and on Rio Roosevelt belonging to Madeira River basin (Dos Anjos et al., 2016) in an area with deforestation and gold-digging, studies showed higher concentrations of mercury compared to data from present study (Table 6). There are studies showing higher mercury concentrations than present study for *H. armatus* with its counterpart *Hydrolycus scomberoides* in Tocantins River in an area with gold-digging and deforestation (Milhomem-Filho et al., 2016), in Tapajós River in an area with gold-digging, deforestation and agriculture (Bidone et al., 1997), on Teles Pires River in an area with gold-digging and deforestation (Uryu et al., 2001). However, other studies have lower concentrations of mercury than those in present study for *H. armatus* in Teles Pires River in an area with deforestation, gold-digging, and agriculture (Matos, 2018) and in a preserved area (Castilhos et al., 2012; Table 6). And for *S. rhombus*, we also found studies with higher concentrations of mercury in Tapajós River in an area with deforestation, gold-digging, and agriculture (Da Silva et al., 2006) and lower concentrations in Tapajós River in an area with deforestation, gold-digging, and agriculture (Bidone et al., 1997), on Teles Pires River in a preserved area (Castilhos et al., 2012) and in an area with gold-digging and deforestation (Uryu et al., 2002; Table 6). These variations in mercury concentration in ichthyofauna can be explained by seasonal migrations of fish, introducing food variations not only temporal but also spatial (Goulding, 1980). Dynamics of Tapajós basin, due to seasonal flooding process, can cause changes in fish feeding and facilitate development of favorable conditions for MeHg production (Roulet et al., 2000). The effects of hydro dams on the increased

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**Table 4.** Amplitude of adverse health effects risk index (RI) calculated for four classes of fish consumers, based on oral reference dose of 0.0003 mg/kg/day/MeHg. DOI: https://doi.org/10.1525/elementa.2021.020.t4

| Species       | Urban Population in State of Mato Grosso (Brazil) | Adult Population with Sporadic Fish Consumption | Adult Population with Frequent Fish Consumption | Riverside and Indigenous Populations in State of Mato Grosso (Brazil) |
|---------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| *B. cuvieri*  | 0.007–0.234                                     | 0.025–0.782                                     | 0.121–3.705                                     | 0.291–8.872                                     |
| *S. rhombus*  | 0.033–0.236                                     | 0.111–0.782                                     | 0.527–3.732                                     | 1.262–8.937                                     |
| *H. armatus*  | 0.024–0.204                                     | 0.081–0.680                                     | 0.385–3.218                                     | 0.922–7.706                                     |

Risk index values were calculated based on amplitude of MeHg concentrations estimated in fish collected from Teles Pires River, described in Table 3.

**Table 5.** Amplitude of adverse health effects risk index (RI) calculated for four classes of fish consumers, based on oral reference dose of 0.0001 mg/kg/day/MeHg for sensitive groups (lactating women, breastfeeding infants and children). DOI: https://doi.org/10.1525/elementa.2021.020.t5

| Species       | Urban Population in State of Mato Grosso (Brazil) | Adult Population with Sporadic Fish Consumption | Adult Population with Frequent Fish Consumption | Riverside and Indigenous Populations in State of Mato Grosso (Brazil) |
|---------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| *B. cuvieri*  | 0.023–0.704                                     | 0.077–2.348                                     | 0.365–11.116                                    | 0.874–26.617                                    |
| *S. rhombus*  | 0.100–0.709                                     | 0.334–2.365                                     | 1.582–11.197                                    | 3.788–26.811                                    |
| *H. armatus*  | 0.073–0.612                                     | 0.244–2.040                                     | 1.156–9.656                                     | 2.768–23.120                                    |

Risk index values were calculated based on amplitude of MeHg concentrations estimated in fish collected from Teles Pires River, described in Table 3.
production of MeHg and bioaccumulation in fish are not fully understood in the Amazon yet. The results of this study provide a baseline for THg and MeHg prior to flooding, to which future studies can be compared against to establish increased rates in Hg bioaccumulation after damming the Teles Pires River.

The effect of hydro dam construction on mercury methylation, bioaccumulation in fish, and exposure to humans is of concern in the Amazon. Approximately 80% of the hydroelectric reservoirs in South America had MeHg levels in predatory fish above the limit (0.5 mg/kg–1 WHO, 2006) desirable for human consumption (Pestana et al., 2019). Several of these reservoirs are located in the Amazon (Malm et al., 2004; Dominique et al., 2007; Kasper et al., 2012; Kasper et al., 2014). In the Manuel Hydroelectric on the Jamari River, an average 1.366 mg/kg MeHG was reported of carnivorous fish downstream and 0.545 mg/kg upstream the dam (Kasper et al., 2012). Particularly for the Teles Pires River, methylation of mercury is further favored by the historical of anthropogenic activities and the recent implantation of a hydroelectric complex, consequently increasing Hg exposure to humans who consume fish from this river.

The average mercury concentration in fish analyzed in the present study is below limit of 0.5 mg/kg –1 recommended by WHO (2006) for fish intake. However, four individual samples have exceeded the WHO recommended mercury limit: two S. rhombeus (0.514 and 0.659 mg/kg –1), one B. cuvieri specimen (0.609 mg/kg –1), and one H. armatus (0.529 mg/kg –1; supplementary material). Although this study comprises a small n-sample, the mercury concentrations analyzed provide a unique data set of mercury concentrations in fish prior to damming the Teles Pires River for the formation of the Colı´der Hydroelectric Reservoir. These results can be used as a baseline to compare mercury concentrations in fish after damming the river, to better understand the increase ratio of MeHg in fish, and consequently on humans consuming fish collected in this region.

In 2011, construction of Colı´der Hydro dam began, filling reservoir in August 2017 with an area of about 182 km 2, about 65 % of reservoir area was forest, and only 70 % of this area had its vegetation removed (CO-PEL, 2018; Matos et al., 2020). Vegetation that has been submerged after filling reservoir can increase concentration of dissolved organic matter in reservoir. Hydroelectric reservoirs in the Amazon region are extremely favorable environments for mercury methylation, as this process is favored in anoxic or suboxide, slightly acidic aquatic environments, with high concentrations of dissolved organic matter and intense microbiological activity (Lacerda and Malm, 2008). Elemental mercury (nonpoisonous) is naturally present in Amazonian soils, having millions of years of existence. Amazonian soils have accumulated mercury received from rain over time

### Table 6. Average THg concentrations (mg/kg wet weight) in species of fishes in Amazon basin reported in literature. DOI: https://doi.org/10.1525/elementa.2021.020.t6

| Species                | THg Concentration | Location        | Possible Hg Source                                | Investigator and Year |
|------------------------|------------------|-----------------|--------------------------------------------------|-----------------------|
| Serrasalmus sp         | 0.100            | Tapajos river   | Gold-digging, deforestation and agriculture       | Bidone et al. (1997)  |
| Hydrolycus tatauaia    | 0.180            | Teles Pires river | Gold-digging, deforestation and agriculture       | Matos (2018)         |
| Hydrolycus sp          | 0.193            | Teles Pires river | Preserved area                                  | Castilhos et al. (2012) |
| Boulengerella cuvieri  | 0.199            | Teles Pires river | Gold-digging, deforestation, and agriculture     | This study            |
| B. cuvieri             | 0.205            | Teles Pires river | Preserved area                                  | Castilhos et al. (2012) |
| Hydrolycus armatus     | 0.229            | Teles Pires river | Gold-digging, deforestation and agriculture      | This study            |
| Serrasalmus sp         | 0.240            | Teles Pires river | Preserved area                                  | Castilhos et al. (2012) |
| Serrasalmus sp         | 0.259            | Teles Pires river | Gold-digging and deforestation                   | Uryu et al. (2002)    |
| Hydrolycus scomberoides| 0.275            | Tocantis river  | Gold-digging and deforestation                   | Milhomem-Filho et al. (2016) |
| Serrasalmus rhombeus   | 0.304            | Teles Pires river | Gold-digging and deforestation                   | This study            |
| S. rhombeus            | 0.383            | Tapajos river   | Gold-digging, deforestation and agriculture      | Da Silva et al. (2006) |
| B. cuvieri             | 0.600            | Roosevelt river | Gold-digging and deforestation                   | Dos anjos et al. (2016) |
| H. scomberoides        | 0.690            | Tapajos river   | Gold-digging, deforestation and agriculture      | Bidone et al. (1997)  |
| H. scomberoides        | 1.650            | Teles Pires river | Gold-digging and deforestation                   | Uryu et al. (2001)    |
due to volcanic eruptions (Fearnside, 2019). The problem of methylation in mercury in this reservoir is aggravated by the fact that the Colider Hydro dam is immediately downstream of another hydroelectric plant (Matos et al., 2020), Sinop Hydro dam, and this is considered a gigantic environmental problem in several aspects (Fearnside, 2019). Thus, in the Colider Hydro dam, there may be a considerable increase in concentrations of MeHg, due to sum of MeHg generated in its reservoir and that originating from Sinop Hydro dam reservoir, because in many cases (Malm et al., 2004; Kasper et al., 2012; Kasper et al., 2014), ichthyofauna downstream is more contaminated with MeHg than that upstream. Results of this research can serve as a database, so that in future, research on effect of flooding of hydro dam can be compared.

4.2. RI for fish consumption

This research presents risks of adverse health effects for two distinct groups: general population and sensitive groups (lactating, infants, and children), according to oral RID for each group indicated by WHO (2006, 2008). For each group, four classes of fish consumption were calculated, ranging from 9 g/day to 340 g/day (Table 2). For four classes of fish consumption within general population group, RI ranged from 0 to 8 (Table 4). Only for classes “Urban population in State of Mato Grosso (Brazil) that rarely consumes fish” (9 g/day) and “Adult population with sporadic fish consumption” (30 g/day), amplitude of RI < 0, is there indication that there is no health risk. For general population (except sensitive groups), including four consumption classes presented in this research, consumption should be at most about 210 g fish per week, or 840 g per month, as up to this intake limit of fish, our results suggest that there is no risk of adverse effects on health (Table 4).

Limit of 0.5 mg/kg·d (WHO, 2006) considers a 60 kg person with a weekly intake of 250 g of fish, reaching an intake of 0.3 μg of MeHg per kg of body weight per day. For sensitive groups (e.g., lactating women, breastfeeding infants, and children), WHO guidelines recommend maximum intake of 0.1 μg of MeHg per kg of body weight per day. In this study, for four classes of fish consumption within sensitive groups, RI ranged from 0 to 26 (Table 5). Only for class “Urban population in State of Mato Grosso (Brazil) that rarely consumes fish” (9 g/day) amplitude of the RI < 0, there is an indication that there is no risk to health. This suggests that people belonging to sensitive group are at greater risk of adverse health effects from mercury poisoning. Therefore, for people in sensitive group, a maximum consumption of 200 g of fish per month is recommended.

Mercury contamination in humans mainly occurs through food intake. Due to the fact that MeHg is a fat soluble, the higher the levels of MeHg in muscle of fish, the greater the chances of contamination in humans, if consumption of fish is in large quantities or frequently. The high RI (0.291–26.811) calculated for class 04 (River-side and indigenous populations in State of Mato Grosso, Brazil) in both groups (general population and sensitive groups) is in agreement with the fish consumption rate reported for three indigenous ethnic groups (Munduruku, Kayabí, and Apiakás) living in the Teles Pires River region. A daily intake of 340 g of fish, including carnivorous species, was reported for these three indigenous groups (Passos et al., 2007; Fany, 2011). Mercury measurements of human hair have shown that 60% of an indigenous Kayabi population had mercury concentrations in hair above the acceptable limit of 10 ppm established by the WHO (Klautau-Guimarães et al., 2005). This is particularly the case for the fishermen colony in the Teles Pires River, the site of this study, which houses 250 professional fishermen whose fish intake and commerce are their main food and income sources.

This pilot study on risk of mercury exposure for traditional communities through fish consumption indicates that further studies are needed to establish with greater precision health effects posed upon these communities. Considering the great nutritional value of fish meat, we suggest that consumption of fish is preferably for noncarnivorous fish. Future studies should consider other fish species commonly consumed in the area and consider biological factors (fish size and diet) in health assessment for human consumption.

5. Conclusion

Almost every fish species analyzed (S. rhombus, B. cuvieri, and H. armatus) presented MeHg concentrations below that recommended for human consumption by WHO, but, considering that region consumes high quantities of fish, the population’s daily MeHg intake can exceed the recommended threshold. Risk indices indicate that for sensitive groups (lactating mothers, infants, and children), consumption of these fish species is only safe in an amount of approximately 200 g per month, and for other consumers, approximately 1,000 g per month can be ingested. However, benefits provided by intake of omega-3 fatty acids present in fish are extremely important. Thus, consumed species, intake frequency, and amount of fish ingested must be taken into account in order to balance benefits and risks of regular fish consumption. Considering high nutritional value of fish meat, we suggest that populations in the study region should choose to consume noncarnivorous fish.

As already presented in the present study, methylation of mercury in aquatic environments is intensified with formation of reservoir lakes as part of hydroelectric plants. Considering that fish analyzed in this research were collected before the formation of reservoir lake for hydroelectric plant Colider Hydro dam, results presented here can serve as a database for monitoring concentration of MeHg in ichthyofauna of Teles Pires River.

Data accessibility statement

Results presented are based on original data sets provided as the Supplemental Data file.

Supplemental files

The supplemental files for this article can be found as follows:
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Author contributions
Conception, design and basic idea of manuscript. Wrote article: MLS.

Collections and biometrics of analyzed fish. Creation and maintenance of database: CASAS.

Project coordinator who raised financial resources to carry out this research: SSAA.

Collections and biometrics of analyzed fish. Critical review as to scientific writing of manuscript: SSAA.

Laboratory analysis of mercury and writing of final version of manuscript: MCC.

Laboratory analysis of mercury and writing of final version of manuscript: IARA.

References
Agostinho, CS, Júlio Jr, HF. 2002. Observation of an invasion of the piranha Serrasalmus marginatus Valenciennes, 1847 (Osteichthyes, Serrasalmidae) into the Upper Paraná River. *Acta Scientiarum* 24(2): 391–395. Available at http://repositorio.uem.br:8080/jpui/bitstream/1/5245/1/374.pdf.

Akagi, H, Malm, O, Kinjo, Y, Harada, M, Branches, FJP, Pfeiffer, WC, Kate, H. 1995. Methylmercury pollution in the Amazon, Brazil. *Science of the Total Environment* 175: 85–95. DOI: http://dx.doi.org/10.1016/0048-9697(95)04905-3.

American Veterinary Medical Association. 2001. Report of the AVMA panel on Euthanasia. *Journal of the American Veterinary Medical Association* 218(5): 669–696. Available at https://www.avma.org/resources-tools/avma-policies/avma-guidelines-euthanasia-animals.

Anim-Gyampo, M, Kumi, M, Zango, MS. 2013. Heavy metals concentrations in some selected fish species in Tono Irrigation Reservoir in Navrongo, Ghana. *Journal of Environment and Earth Science* 3: 109–119. Available at https://www.iiste.org/Journals/index.php/JeEs/article/view/4013.

Azevedo-Silva, CE, Almeida, R, Carvalho, DP, Ometto, JP HB, Camargo, PB, Dorneles, PR, Azeredo, A, Bastos, WR, Malm, O, Torres, JPM. 2016. Mercury biomagnification and the trophic structure of the ichthyofauna from a remote lake in the Brazilian Amazon. *Environmental Research* 151: 286–296. DOI: http://dx.doi.org/10.1016/j.envres.2016.07.035.

Barbosa, TAP, Rosa, DCO, Soares, BE, Costa, CHA, Esposito, MC, Montag, LFA. 2018. Effect of flood pulses on the trophic ecology of four piscivorous fishes from the eastern Amazon. *Journal of Fish Biology* 93(1): 30–39. DOI: http://dx.doi.org/10.1111/jfb.13669.

Bastos, WR, Dórea, JG, Bernardi, JV, Lauthartte, LC, Mussy, MH, Lacerda, LD, Malm, O. 2015. Mercury in fish of the Madeira River (temporal and spatial assessment), Brazilian Amazon. *Environmental Research* 140: 191–197. DOI: http://dx.doi.org/10.1016/j.envres.2015.03.029.

Bastos, WR, Malm, O, Pfeiffer, WC, Cleary, D. 1998. Establishment and analytical quality control of laboratories for Hg determination in biological and geological samples in the Amazon, Brazil. Ciênc. Cult 50: 255–260. Available at https://pesquisa.bvsalud.org/portal/resource/pt/ll/262165?lang=en.

Bidone, E, Castilhos, Z, Cid de Souza, T, Lacerda, LD. 1997. Fish contamination and human exposure to Mercury in the Tapajós river basin, Pará State, Amazon, Brazil: A screening approach. *Bulletin of Environmental Contamination and Toxicology* 59: 194–201. DOI: http://dx.doi.org/10.1007/s001289900464.

Bisinoti, MC, Jardim, WF. 2004. O comportamento do metilmercúrio (MeHg) no ambiente. *Quim. Nova* 27(4): 593–600. DOI: http://dx.doi.org/10.1590/S0100-4042200400400014.

Bloom, NS. 1992. On the chemical form of mercury in edible fish and marine invertebrate tissue. *Canadian Journal of Fisheries and Aquatic Sciences* 49(5): 1010–1017. Available at http://www.nrcresearchpress.com/doi/abs/10.1139/f92-113.

Campbell, KR. 1994. Concentrations of heavy metals associated with urban runoff in fish living in storm water treatment ponds. *Archives of Environmental Contamination and Toxicology* 27: 352–356. Available at https://link.springer.com/article/10.1007/BF00213171.

Castilhos, Z, Cesar, R, Colonese, J, Egler, S, Araújo, P, Feilzmann, W, Merten, G, Rocha, B, Touche, S. 2012. Ecorregiões Aquáticas Xingu-Tapajós: Caracterização das águas superficiais e teores de mercúrio em sedimentos e em peixes. Centro de Tecnologia Mineral. Ministério da Ciência, Tecnologia e Inovação. Coordenação de Processos Minerais – COPM: 103–138.

Castro, NSS, Braga, CM, Trindade, PAA, Giarrizzo, T, Lima, MO. 2016. Mercury in fish and sediment of Purus River, Acre State, Amazon. *Cadernos Saúde
Coletiva 24(3): 294–300. DOI: http://dx.doi.org/10.1590/1414-462x201600030142.

Copat, C, Bella, F, Castaing, M, Fallico, R, Sciaccia, S, Ferrante, M. 2012. Heavy metals concentrations in fish from Sicily (Mediterranean Sea) and evaluation of possible health risks to consumers. Bulletin of Environmental Contamination and Toxicology 88: 78–83. DOI: http://dx.doi.org/10.1007/s00128-011-0433-6.

COPEL – Companhia Paranaense de energia. 2018. Relatório mensal do Subprograma de Controle das Atividades de Supressão de Vegetação da UHE-Colider, fevereiro, 6 p.

Cordeiro, RC, Turcq, B, Ribeiro, MG, Lacerda, LD, Capitanéo, J, Oliveira da Silva, A, Sifeddine, A, Turcq, PM. 2002. Forest fire indicators and mercury deposition in an intense land use change region in the Brazilian Amazon (Alta Floresta, MT). The Science of the Total Environment 293: 247–256. DOI: http://dx.doi.org/10.1016/S0048-9697(02)00045-1.

Dary, EP, Ferreira, E, Zuanon, J, Röpke, CP. 2017. Diet and trophic structure of the fish assemblage in the mid-course of the Teles Pires River, Tapajós River basin, Brazil. Neotropical Ichthyology 15(4): e160173. DOI: http://dx.doi.org/10.1590/1982-0224-20160173.

Da Silva, DS, Lucotte, M, Roulet, M, Poirier, H, Merget, D, Crossa, M. 2006. Mercúrio nos Peixes do Rio Tapajós, Amazônia Brasileira. Interfase EHS 1(1): 1–31. Available at http://dx.doi.org/doi://www.interfacehs.sp.senac.br/br/artigos.asp?ed=1&cod_artigo=6.

Dominique, Y, Maury-Brachet, R, Muresan, B, Vigouroux, R, Richard, S, Cossa, D, Mariotti, A, Boudou, A. 2007. Biofilm and Mercury availability as key factors for mercury accumulation in fish (Curimata cyprinoids) from a disturbed Amazonian freshwater system. Environmental Toxicology and Chemistry 26: 45–52. DOI: http://dx.doi.org/10.1897/05-649R.1.

Dos Anjos, MR, Machado, NG, Da Silva, MEP, Bastos, WR, Miranda, MR, Carvalho, DP, Mussy, MH, Holland, IB, Biudes, MS, Fulan, JA. 2016. Bioaccumulation of methylmercury in fish tissue from the Roosevelt River, Southwestern Amazon basin. Revista Ambiente & Água 11(3): 508–518. DOI: http://dx.doi.org/10.4136/ambi-agua.1830.

Fany, R. 2011. Povos indígenas no Brasil 2006/2010. 1ª edição. São Paulo, Brazil: Editora Instituto Socioambiental: 778.

FAO/WHO. 2006. Meeting of the joint FAO/WHO expert committee on food additives. Rome. Summary and conclusions . . . Rome: FAO: 11p. Available at http://www.fao.org/3/a0675e/a0675e00.pdf.

Fearnside, PM. 2019. Hidrelétricas na Amazônia: Impactos ambientais e sociais na tomada de decisões sobre grandes obras. Manaus, Brazil: Editora do INPA. v. 3, 148 p.

Flotemersch, JE, Stribling, JB, Paul, MJ, Snyder, BD. 2006. Fish, in Flotemersch, JE, Stribling, JB, Paul, MJ eds., Concepts and approaches for the bioassessment of non-wadeable streams and rivers. Cincinnati, OH: USEPA: 7.1–7.26.

Goulding, M. 1980. The fishes and the forest. Explorations in Amazonian natural history. Berkeley, CA: University of California Press: 280.

Hosseini, M, Nabavi, SM, Parsa Y. 2013. Bioaccumulation of trace mercury in trophic levels of benthic, benthopelagic, pelagic fish species, and sea birds from Arvand River, Iran. Biological Trace Element Research 156(1–3): 175–180. DOI: http://dx.doi.org/10.1007/s12011-013-9841-2.

Instituto Brasileiro De Geografia e Estatística. 2011. Pesquisa de orçamentos familiares 2008–2009: Análise do consumo alimentar pessoal no Brasil/IBGE, Coordenação de trabalho e Rendimento. Rio de Janeiro. Available at https://biblioteca.ibge.gov.br/visualizacao/livros/liv50063.pdf.

Kasper, D, Forsberg BR, Amaral JHF, Leitão RP, Py-Daniel SS, Bastos, WR, Malm, O. 2014. Reservoir stratification affects methylmercury levels in river water, plankton, and fish downstream from Balbina Hydroelectric Dam, Amazonas, Brazil. Environmental Science and Technology 48: 1032–1040. DOI: http://dx.doi.org/10.1021/es4042644.

Kasper, D, Palermo, EFA, Branco, CWC, Malm, O. 2012. Evidence of elevated mercury levels in carnivorous and omnivorous fishes downstream from an Amazon reservoir. Hydrobiologia 694: 87–98. DOI: http://dx.doi.org/10.1007/s10750-012-1133-x.

Kehrig, HA, Howard, BM, Malm, O. 2008. Methylmercury in a predatory fish (Cichla spp.) inhabiting the Brazilian Amazon. Environmental Pollution 154(1): 68–76. DOI: http://dx.doi.org/10.1016/j.envpol.2007.12.038.

Kidwell, JM, Phillips, LJ, Birchard, GF. 1995. Comparative analyses of contaminant levels in bottom feeding and predatory fish using the national contaminant biomonitoring program data. Bulletin of Environmental Contamination and Toxicology 54: 919–923. DOI: http://dx.doi.org/10.1007/bf01979797.

Klautau-Guimarães, MN, D’Ascencio, R, Caldart, FA, Grisolia, CK, Souza, JR, Barbosa, AC, Cordeiro, CMT, Ferrari, I. 2005. Analysis of genetic susceptibility to mercury contamination evaluated through molecular biomarkers in at-risk Amazon Amerindian populations. Genetics and Molecular Biology 28: 827–832. DOI: http://dx.doi.org/10.1590/S1415-47572005000500027.

Lacerda, LD, Malm, O. 2008. Mercury contamination in aquatic ecosystems: An analysis of the critical areas. Estudos Avançados 22(63): 173–90. DOI: http://dx.doi.org/10.1590/S1415-47572005000500027.

Latrubesse, EM, Arima, EY, Dunne, T, Park, E, Baker, VR, Horta, FM, Wight, C, Wittmann, F, Zuanon, J, Baker, PA, Ribas, CC, Norgaard, RB, Filizola, N, Ansar, A, Flyvbjerg, B, Stevaux, JC. 2017.
Damming the rivers of the Amazon basin. Nature 546: 363–369. DOI: http://dx.doi.org/10.1038/nature22333.

Lechler, PJ, Miller, JR, Lacerda, LD, Vinson, D, Bonzongo, JC, Lyons, WB, Warwick, JJ. 2000. Elevated mercury concentrations in soils, sediments, water, and fish of the Madeira river basin, Brazilian Amazon: A function of natural enrichments? Science of the Total Environment 260: 87–96. DOI: http://dx.doi.org/10.1016/S0048-9697(00)00543-X.

Lino, AS, Kasper, D, Guida, YS, Thomaz, JR, Malm, O. 2018. Mercury and selenium in fishes from the Tapajós River in the Brazilian Amazon: An evaluation of human exposure. Journal of Trace Elements in Medicine and Biology 48: 196–201. DOI: http://dx.doi.org/10.1016/j.jtemb.2018.04.012.

Lobo, FL, Costa, M, Novo, EMLM, Telmer, K. 2016. Distribution of artisanal and small-scale gold mining in the Tapajós River Basin (Brazilian Amazon) over the past 40 years and relationship with water siltation. Remote Sensing 8: 579–601. Available at http://www.mdpi.com/2072-4292/8/7/579.

Malm, O, Branches, FJP, Akagi, H, Castro, MB, Pfeiffer, WC, Harada, M, Bastos, WR, Kato, H. 1995. Mercury and methylmercury in fish and human hair from the Tapajós River basin, Brazil. Science of the Total Environment 175: 141–150. DOI: http://dx.doi.org/10.1016/0048-9697(95)04910-X.

Malm, O, Guimarães, JRD, Castro, MB, Bastos, WR, Viana, JP, Branches, FJP, Silveira, EG, Pfeiffer, WC. 1997. Follow-up of mercury levels in fish, human hair and urine in the Madeira and Tapajós basins, Amazon, Brazil. Water, Air, & Soil Pollution 97: 45–51. DOI: http://dx.doi.org/10.1007/BF02409643.

Malm, O, Palermo, EFA, Santos, HSB, Rebelo, MF, Kehrig, HA, Oliveira, RB, Meire, RO, Pinto, FN, Moreira, LPA, Guimarães, JRD, Torres, JPM, Pfeiffer, WC. 2004. Transport and cycling of mercury in the Curiqui reservoir, Amazon, Brazil: 20 years after fulfill- ment. RMZ – Materials Geoenviron 51: 1195–1198.

Matos, LS. 2018. Perturbações antrópicas em espécies alvo da icitofauna da bacia do rio Teles Pires. Tese (doutorado) - Universidade Federal de Mato Grosso, Instituto de Biociências, Programa de Pós-Graduação em Ecologia e Conservação da Biodiversidade, Cuiabá/MT, 143 p.

Matos, LS, Santana, HS, Silva, JOS, Carvalho, LN. 2020. Perception of professional artesanal fisherman on the decline in the catch of matrixá fish in the Teles Pires River, Tapajós Basin. DOI 10.22533/at.ed.65020280510. IN: Padrões Ambientais Emergentes e Sustentabilidade dos Sistemas. Organizadora Jésica Aparecida Prandel. Ponta Grossa, PR: Atena. DOI 10.22533/at.ed.650202805.

Matos, LS, Silva, JOS, Kasper, D, Carvalho, LN. 2018. Assessment of mercury contamination in Brycon falcatus (Characiformes: Bryconidae) and human health risk by consumption of this fish from the Teles Pires River, Southern Amazonia. Neotropical Ichthyology 16(1): e160106. DOI: http://dx.doi.org/10.1590/1982-0224.20160106.

Micaroni, RCM, Bueno, MIMS, Jardim, WF. 2000. Compostos de mercúrio. Revisão de métodos de determinação, tratamento e descarte. Quimica Nova 23: 487–495. DOI: http://dx.doi.org/10.1590/S0100-40422000000400011.

Milhomem-Filho, EO, Oliveira, CSB, Silveira, LCL, Cruz, TM, Souza, GS, Costa-Junior, JMF, Pinheiro, MCN. 2016. The intake of fish and the mercury concentration of fishing families at the city of Imperatriz (MA). Revista Brasileira de Epidemiologia 19(1): 14–25. DOI: http://dx.doi.org/10.1590/1980-5497.201600010002.

Opaaluwa, OD, Aremu, MO, Ogbo, LO, Magaji, JI, Odiba, IE, Ekpo, ER. 2012. Assessment of heavy metals in water, fish and sediments from UKE Stream, Nasarawa State, Nigeria. Current World Environment 7(2): 213–220. DOI: http://dx.doi.org/10.12944/CWE.7.204.

Passos, CJS, Mergler, D, Lemire, M, Fillion: J, Guimarães, JRD. 2007. Fish consumption and bioindicators of inorganic mercury exposure. Science of the Total Environment 373: 68–76. DOI: http://dx.doi.org/10.1016/j.scitotenv.2006.11.015.

Pereira, JGM, De Lima, MG, Bellaver, SM, Schuings, CO, Costa, GM. 2012. Análise morfológica do estômago de Boulangrella cuvieri (TELEOSTEI: CTENO-LUCIDAE), bicuda. Revista de Ciências Agronômicas da FURG 10(1): 93–98. Available at https://docplayer.com.br/8822134-Analise-morfologica-do-estomago-de-boulangrella-cuvier-teleosti-ctenolucidae-bicuda.html.

Pestana, IA, Azevedo, LS, Bastos, WR, de Souza, CMM. 2019. The impact of hydroelectric dams on mercury dynamics in South America: A review. Chemosphere 219: 546–556. DOI: http://dx.doi.org/10.1016/j.chemosphere.2018.12.035.

Picoli, F. 2004. Amazônia: do mel ao sangue – os extremos da expansão capitalista. Editora Amazônia, Sinop, Brazil, 125 p.

Piorkski, NM, Alves, JRL, Machado, MRB, Correia, MMA. 2005. Alimentação e ecomorfológia de duas espécies de piranhas (Characiformes: Characidae) do lago de Viana, estado do Maranhão, Brasil. Acta Amazônica 35(1): 63–70. Available at https://www.scielo.br/pdf/aa/v35n1/35n1a09.pdf.

Pirrone, N, Cinnirella, S, Feng, X, Finkelman, RB, Friedli, HR, Leaner, J, Mason, R, Mukherjee, AB, Strachrer, G, Streets, DG, Telmer, K. 2010. Global Mercury emissions to the atmosphere from natural and anthropogenic sources. Atmospheric Chemistry and Physics 10: 5951–5964. DOI: http://dx.doi.org/10.5194/acp-10-5951-2010.

Porcela, DB. 1994. Mercury in the environment: Biogeochemistry, in Watras CJ, Huckabee, JW eds., Mercury pollution: Integration and synthesis. Boca Raton, FL: Lewis Publishers: 2–7.

Pouilly, M, Perez, T, Rejas, D, Guzman, F, Crespo, G, Duprey, JL, Guimarães, JRD. 2012. Mercury
bioaccumulation patterns in fish from the Iténez river basin, Bolivian Amazon. *Ecotoxicology and Environmental Safety* 83: 8–15. DOI: http://dx.doi.org/10.1016/j.ecoenv.2012.05.018.

R Core Team. 2020. A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. Available at http://www.R-project.org/.

Roulet, M, Lucotte, M, Canuel, R, Farella, N, Courcelles, M, Guimaraes, JRD, Mergler, JRD, Amorim, M. 2000. Increase in mercury contamination recorded in lacustrine sediments following deforestation in the central Amazon. *Chemical Geology* 165: 243–266. DOI: http://dx.doi.org/10.1016/S0009-2541(99)00172-2.

Santos, GM, Ferreira, EJG, Zuanon, JAS. 2006. Peixes comerciais de Manaus, Ibama/AM, ProVarzea. Manaus, Brazil, 144 p. Available at https://repositorio.inpa.gov.br/handle/1/4700.

Santos, GM, Merona, B, Juras, AA, Jégu, M. 2004. Peixes do baixo rio Tocantins: 20 anos depois da Usina Hidrelétrica de Tucuruí. Brasilia: Eletronorte: 216.

Shao, D, Kang, Y, Wu, S, Wong, MH. 2012. Effects of sulfate reducing bacteria and sulfate concentrations on mercury methylation in freshwater sediments. *Science of the Total Environment* 424: 331–336. DOI: http://dx.doi.org/10.1016/j.scitotenv.2011.09.042.

Sundseth, K, Pacyna, JM, Pacyna, EG, Pirrone, N, Thorne, RJ. 2017. Global sources and pathways of Mercury in the context of human health. *International Journal of Environmental Research and Public Health* 14(1): 105. DOI: http://dx.doi.org/10.3390/ijerph14010105.

Terra, BF, Araújo, FG, Calza, CF, Lopes, RT, Teixeira, TP. 2008. Heavy metal in tissues of three fish species from different trophic levels in a tropical Brazilian River. *Water, Air, & Soil Pollution* 187: 275–284. Available at https://link.springer.com/article/10.1007/s11270-007-9515-9.

Uryu, Y, Malm, O, Thornton, I, Payne, I, Cleary, D. 2001. Mercury contamination of fish and its implications for other wildlife of the Tapajós Basin, Brazilian Amazon. *Conservation Biology* 15: 438–446. DOI: http://dx.doi.org/10.1046/j.1523-1739.2001.015002438.x.

U.S. Environmental Protection Agency. 2000. Guidance for Assessing Chemical Contamination Data for Use in Fish Advisories. Volume 1: Fish Sampling and Analysis, and Volume 2: Risk Assessment and Fish Consumption Limits. U.S. Environmental Protection Agency Report EPA 823-B-97-009, third edition. Cincinnati, OH. Available at https://www.epa.gov/sites/production/files/2015-06/documents/volume1.pdf and https://www.epa.gov/sites/production/files/2015-06/documents/volume2.pdf.

U.S. Environmental Protection Agency. 2010. Guidance for Implementing the January 2001 Methylmercury Water Quality Criterion. EPA 823-R-10-001. Washington, DC: U.S. Environmental Protection Agency, Office of Water. Available at https://www.epa.gov/sites/production/files/2019-02/documents/guidance-implement-methylmercury-2001.pdf.

Verhaert, V, Teuchies, J, Vlok, W, Wepener, V, Addo-Bediako, A, Jooste, A, Blust, R, Bervoets, L. 2019. Bioaccumulation and trophic transfer of total mercury in the subtropical Olifants River Basin, South Africa. *Chemosphere* 216: 832–843. DOI: http://dx.doi.org/10.1016/j.chemosphere.2018.10.211.

Voigt, HR. 2004. Concentrations of mercury (Hg) and cadmium (Cd), and the condition of some coastal Baltic fishes. *Environmentalatica Fennica* 21: 1–26. Available at https://pdfs.semanticscholar.org/87f2/31c02461ca4e0e2b3757f2f44606dd34b655f.pdf?_ga=2.188038120.1192605157.1582910466-74674291.1580660556.

World Health Organization. 2006. Exposure to mercury: A major public health concern. United Nations Environment Programme. Geneva, Switzerland: World Health Organization: 4.

World Health Organization. 2008. *United Nations Environment Programme. Guidance for identifying populations at risk from mercury exposure.* Geneva, Switzerland: World Health Organization: 180.

Wuana, RA, Okeimen, FE. 2011. Heavy metals in contaminated soils: A review of sources, chemistry, risks and best available strategies for remediation. *ISRN Ecology* 2011: 1–20. DOI: http://dx.doi.org/10.5402/2011/402647.
