



Flood pulse as a driving force of Pb variation in four fish guilds from Puruzinho Lake (western Amazon)

Sophia Menezes de Azevedo¹ · Luiza Silva do Nascimento¹ · Layra de Oliveira Silva¹ · Marcelo Gomes de Almeida¹ · Lucas Silva Azevedo² · Wendel Dias Constantino¹ · Wanderley Rodrigues Bastos³ · Inácio Abreu Pestana¹

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Abstract

The Brazilian Amazon is heavily impacted by mining activities, especially by gold and cassiterite mining. Pb is a contaminant released during cassiterite extraction, and it stands out for its high toxicity. The present study aimed to evaluate the effect of flood pulse on Pb dynamics in four fish species with different feeding habits (*Cichlapleiozona*: carnivorous, *Mylossomaduriventre*: herbivorous, *Prochilodus nigricans*: detritivorous, and *Serrasalmus rhombeus*: piscivorous) over four hydrological periods in Puruzinho Lake (Brazilian Amazon), which receives water from the Madeira River. The risk assessment for daily Pb intake through the consumption of these fish by the local riverside population was also carried out. Fish species were sampled during four Amazonian hydrological periods: rising water, high water, falling water, and low water. Pb and stable isotopes ($\delta^{15}\text{N}$ and $\delta^{13}\text{C}$) measurements were carried out on fish muscle. The flood pulse had the same effect on Pb concentrations of all the fish species regardless of their feeding habits, as we found a nonsignificant interaction between these variables. The Pb in fish muscle increased in the flood season (rising and high water) and decreased in the dry season (falling and low water). The Pb concentration in fish increased significantly with their trophic level ($\delta^{15}\text{N}$), evidencing the occurrence of biomagnification of the element along the trophic chain ($R^2 = 0.24$). The main food source of the herbivorous fish ($\delta^{13}\text{C}$) was very distinct from that of the others, which had a large overlap in their values. Regarding risk assessment, the daily Pb intake through consumption of the herbivorous species during high water ($17.82 \pm 19.68 \mu\text{g}\cdot\text{day}^{-1}$) exceeded the limit determined by the Food and Drug Administration (FDA) of $12.5 \mu\text{g}\cdot\text{day}^{-1}$, representing a health risk to the riverside population of Puruzinho Lake.

Keywords Lead · Amazon · Fish · Feeding habits · Hydrological periods · Risk assessment

Introduction

The Brazilian Amazon is heavily impacted by mining activities, especially by gold and cassiterite mining (Rudke et al. 2020). Although the impacts of gold mining on Hg contamination have been widely studied in the Amazon (e.g., Nriagu et al. 1992; Pfeiffer and Lacerda 1988; Lacerda and Salomons 1998; Bastos et al. 2006; Lacerda and Malm 2008; Guimarães 2020; Pestana et al. 2022), studies on the impacts of cassiterite extraction on the release of contaminants to the environment are still incipient.

The extraction of cassiterite is intense in the Madeira River (Rudke et al. 2020), an important tributary of the Amazon River, especially near the city of Porto Velho (Rondônia State; Longo et al. 2011). Among the contaminants released during cassiterite extraction, Pb stands out for its high toxicity (Stierman et al. 2020; Ishitsuka et al.

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✉ Inácio Abreu Pestana
inacio@uenf.br

¹ Laboratório de Ciências Ambientais, Centro de Biociências E Biotecnologia, Universidade Estadual Do Norte Fluminense Darcy Ribeiro, Av. Alberto Lamego, 2000–Parque Califórnia–CEP, Rio de Janeiro, Campos Dos Goytacazes 28013-602, Brazil

² Divisão de Fauna E Flora, Gerência de Licenciamento, Diretoria de Licenciamento E Outorga, Instituto Água E Terra, Street Engenheiro Reboças, 1206–Reboças–CEP, Curitiba, Paraná 80215-000, Brazil

³ Laboratório de Biogeoquímica Ambiental Wolfgang C. Pfeiffer, Universidade Federal de Rondônia, Av. Pres. Dutra, 2967–Olaria–CEP, Porto Velho, Rondônia 76801-059, Brazil

2020) and accumulation in soils and sediments (Ribeiro et al. 2017). In addition to the point contamination caused by cassiterite mining, Pb also has important diffuse sources of contamination, such as industrial activities and its former use in gasoline; all of which are associated with the atmospheric phase of its biogeochemical cycle (UNEP 2010). The main routes of human exposure to Pb are inhalation and diet (Mushak 2011). Regarding contaminant intake through diet, fish consumption is of great concern in the Amazon, where the estimated consumption is $140 \text{ kg}\cdot\text{person}^{-1}\cdot\text{year}^{-1}$ (Oliveira et al. 2010), 15 times higher than the Brazilian average ($8.9 \text{ kg}\cdot\text{person}^{-1}\cdot\text{year}^{-1}$; Sonoda and Shiota 2012). Given this high intake, even a low level of contamination can cause problems.

As a toxic element, Pb concentrations are monitored in food by Brazil's National Sanitary Surveillance Agency (ANVISA). In commercial fish, the maximum tolerance limit (MTL) is $0.3 \mu\text{g}\cdot\text{g}^{-1}$ (ANVISA 2021). In addition, there is an established daily Pb intake limit that if exceeded can harm human health. The last provisional reference limit established by the Food and Drug Administration (FDA) for daily Pb intake is $3 \mu\text{g}\cdot\text{day}^{-1}$ for children and $12.5 \mu\text{g}\cdot\text{day}^{-1}$ for adults (Dolan et al. 2020; Flannery et al. 2020). Pb intoxication can affect several body functions, especially neurological ones, and is linked to reduced cognitive functions and changes in neurotransmitter secretion (Ishitsuka et al. 2020; Stierman et al. 2020).

Some studies in the Amazon have already reported high levels of Pb exposure in the riverside population (Barbosa-Jr et al. 2009) and cassiterite miners (Hacon et al. 2010; Queiroz et al. 2019). Regarding cassiterite mining, it is clear that the distance from mining areas plays an important role in defining the health risk of populations (Hacon et al. 2010). High cassiterite mining activities are reported in the literature in the Jamari River (Longo et al. 2011), a tributary of the Madeira River. The waste released increases the Pb concentration in the water and can be transported to sedimentation areas like floodplains due to the great transport capacity of these rivers. This has already been observed for other contaminants like Cr, which also has an anthropic source in the Jamari River (tanneries) and whose concentrations increased more than 250 km downstream in the Madeira River until reaching Puruzinho Lake (Sousa et al. 2015; Nascimento et al. 2022).

In the Amazon, the transport capacity of rivers is strongly related to the seasonality of hydrological periods in aquatic ecosystems. Puruzinho Lake is a floodplain lake located in the state of Amazonas (AM) that is heavily influenced by the flood pulse of the Madeira River, to which it is connected by a narrow channel (locally called *igarapé*; Feitosa et al. 2019). The hydrological periods in the Amazon can be divided according to the rivers' depths into rising and high water (which comprise the flood period) and falling

and low water (which represent the dry period). The rising water period starts in October and ends in February; the high water period is established in February and ends in May; the falling water period begins in May and ends in September; the low water season starts in September and ends in October (Azevedo et al. 2020). During the high water period, the Madeira River overflows and its water invades Puruzinho Lake. At that moment, the contaminants present in the water of the Madeira River are transported to the lake (Nascimento et al. 2007) where they then can be absorbed by the biota.

The main route of contaminant absorption by fish is through diet. Depending on the behavior of the contaminant in the food web, biodilution or biomagnification of contaminants can occur (Azevedo et al. 2020; Nascimento et al. 2022). In the latter case, it directly impacts the health of the exposed riverside population and can be investigated through the use of stable isotopes. The stable isotope of carbon ($\delta^{13}\text{C}$) is commonly used to determine the source of the organic matter of an aquatic environment or organisms, such as fish, being fractionated mainly by photosynthetic activity and decomposition of organic matter (Fry 2006), while the stable isotope of nitrogen ($\delta^{15}\text{N}$) varies on average from 3 to 4‰ per trophic level, so its values can be used for studies on trophic relationships among living beings (Fry 2006).

The aim of this study was to evaluate the effects of the Madeira River flood pulse on the Pb dynamics in four fish species with different feeding habits in Puruzinho Lake, western Amazon. We also evaluated the risk of Pb intake through fish consumption by the riverside population of the region. Our hypothesis was that since the fish are from different trophic guilds, their diets would influence Pb concentrations throughout the four hydrological periods (Azevedo et al. 2020).

Material and methods

Study area

Puruzinho Lake ($63^{\circ}6'0''\text{W}$; $7^{\circ}24'0''\text{S}$) is located near the municipality of Humaitá (Amazon state), on the left bank of the Madeira River, receiving its water during the flood period through an *igarapé* (Fig. 1). This river-floodplain system is common in the Amazon, and our study site is an ideal model for biogeochemical analysis of trace elements, as it has been used in the past for this purpose (Azevedo et al. 2020, 2021; Nascimento et al. 2022).

The Madeira River is classified as a white water ecosystem characterized by brown water, pH close to neutral, and high concentrations of suspended particulate matter (SPM) (Sioli 1968). On the other hand, Puruzinho Lake is considered a black water ecosystem characterized by dark colored water, large amounts of organic matter, and pH tending to

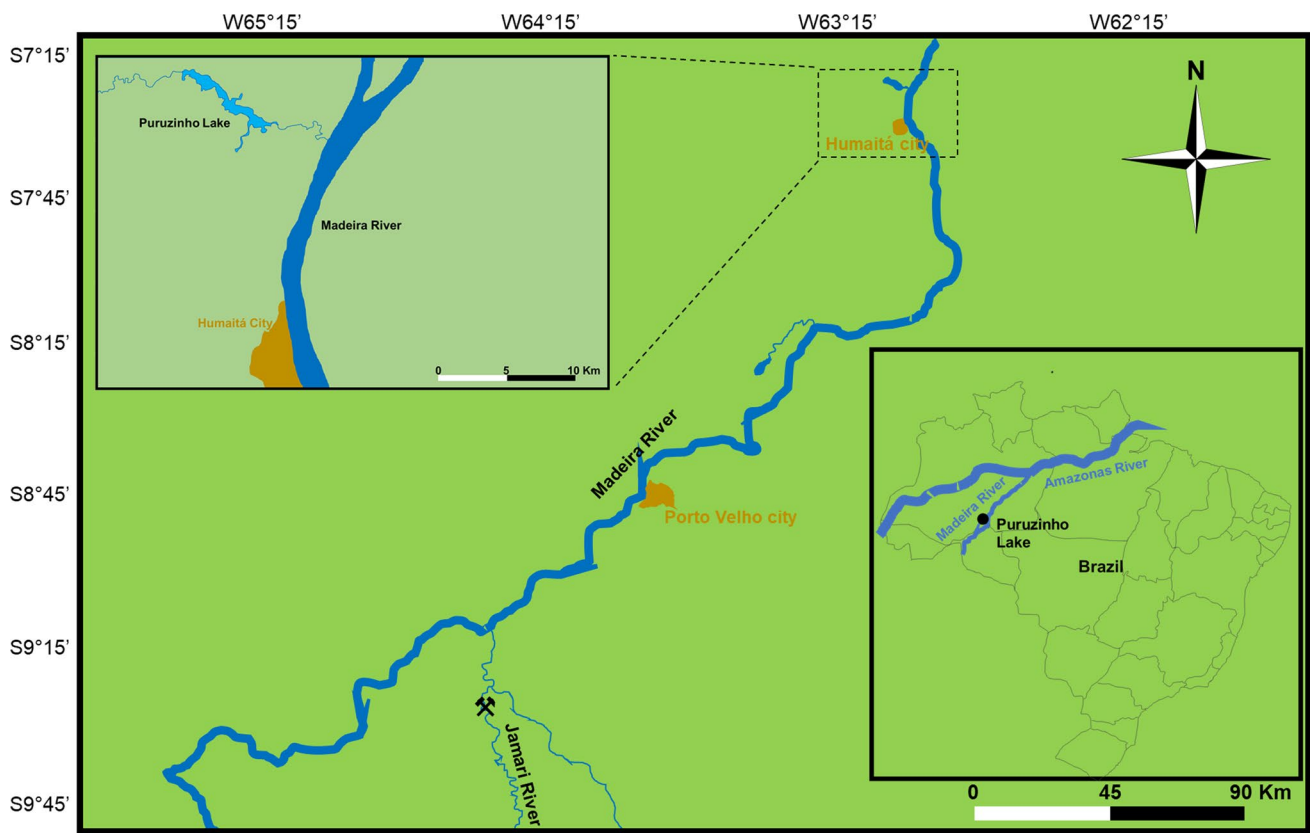


Fig. 1 Puruzinho lake (left inset), located in the state of Amazonas, Brazil, which receives water from the the Madeira River through a narrow channel (*igarapé*). Cassiterite mining was reported to occur in the Jamari River (Longo et al. 2011) and is indicated on the map

acidity (Sioli 1968). This lake is strongly influenced by the hydrological seasonality of the region, and during the high water period, the water column can reach up to 12.5 m in depth, while in the low water period this depth can decrease to only 0.30 m (Almeida et al. 2014; ANA 2019; Supplementary Material 1).

Sampling

The samples used in this study are from a larger project aimed to evaluate the biogeochemistry of trace elements in the Amazon region and have already been used for assessment of Hg and Cr dynamics in fish as well their trophic ecology (Azevedo et al. 2020, 2021; Nascimento et al. 2022). Briefly, fish were sampled with the help of local fishermen at a single point in the lentic part of the lake. Four species with different feeding habits were sampled: *Mylossoma duriventre* (herbivorous, common name “Pacuprata”), *Prochilodus nigricans* (detritivorous, “Curimatã”), *Cichlapleiozona* (carnivorous, “Tucunaréamarelo”), and *Serrasalmus rhombeus* (piscivorous, “Piranha preta”), totaling 268 specimens. For the capture of fish, gillnets with sizes of 30, 45, and 60 mm were used. After capture, the fish

were measured for total length and weight. Also, fish muscle was extracted, freeze-dried (LioTop L108 freeze dryer; São Paulo, Brazil), and reserved for chemical measurements. The sampling was carried out between December 2016 and December 2018 comprising four hydrological periods and four fish species (Table 1, Supplementary Material 1). We defined the feeding habits of the species based on Cella-Ribeiro et al. (2016), who compiled detailed data about the stomach content and biology of several fish species from the Madeira River Basin.

Chemical analyses

Pb measurements

Pb determination was carried out using fish muscle tissue (1.0 g dry weight) as follows (adapted from Bastos et al. 1998): (i) solubilization using 2 mL of 30% hydrogen peroxide (H_2O_2) and 10 mL of 65% nitric acid (HNO_3), (ii) heating in a digester block starting at 60 °C and ending at 120 °C until the complete solubilization of the samples, (iii) reducing the volume to 1 mL at 160 °C, and (iv) filtration with a quantitative filter (Whatman® 40 filter paper) followed

Table 1 Sample size for each species and hydrological period sampled. The scientific names of each species and their feeding habits are also presented

Feeding habits	Herbivorous	Detritivorous	Carnivorous	Piscivorous
Scientific name	<i>Mylossoma duriventre</i>	<i>Prochilodus nigricans</i>	<i>Cichlapleiozona</i>	<i>Serrasalmus rhombeus</i>
Risingwater (February 2017, December 2018)	13	16	6	10
High water (April 2017, April 2018)	20	20	19	10
Falling water (June 2017, June 2018)	25	22	35	20
Low water (October 2017, December 2017)	6	20	12	14

by completing the volume up to 35 mL with 0.5 N HNO₃. The measurements were performed by inductively coupled plasma-optical emission spectrometry (ICP-OES 720 ES; Varian, Australia) with a detection limit of 0.01 µg·g⁻¹ (wet weight) and a 5-point calibration curve (0.02, 0.05, 0.1, 0.5, and 1 µg·mL⁻¹).

The analytical quality control of the samples was evaluated through analytical replicates and blanks and by the certified reference material (DORM-3), whose recovery was 107 ± 9% (n = 3). The Pb concentrations by dry weight were converted into wet weight since the regulatory limits are expressed in this unit. For conversion, the following moisture values were used: 77% water for the species *Cichlapleiozona* (Inhamuns and Franco 2008), 73% for *Mylossomaduriventre* (Melo et al. 2019), 71% for *Prochilodus nigricans* (Inhamuns 2000), and 78% for *Serrasalmus rhombeus* (Hiane et al. 2002).

Stable isotope (δ¹³C and δ¹⁵N) analysis

The stable isotope (δ¹³C and δ¹⁵N) analysis was carried out using a Thermo Finnigan Delta V Advantage mass spectrometer (isotopic ratio mass spectrometer, IRMS; Thermo Fisher Scientific, Milan, Italy) coupled to a Flash 2000 organic elemental analyzer (Thermo Fisher Scientific, Milan, Italy). Pee Dee Belemnite (PDB) and atmospheric nitrogen were used as standards for δ¹³C and δ¹⁵N, respectively. For δ¹³C, the coefficient of variation between replicates was ± 0.2‰, and for δ¹⁵N it was ± 0.3‰. The δ¹³C signature was corrected to remove the influence of lipids (McConnaughey and McRoy 1979; Azevedo et al. 2021).

Risk assessment

The assessment of risk of Pb ingestion through consumption of fish from Puruzinho Lake was calculated using the estimated daily intake (EDI) index (FAO/WHO 2014):

$$EDI = C_{Pb} \cdot I_{fish}$$

where EDI is the estimated daily intake (µg·day⁻¹), C_{Pb} is the Pb concentration determined in the fish samples (µg·g⁻¹

wet weight), and I_{fish} is the intake rate (g·day⁻¹) for each fish species.

The fish intake rate (I_{fish}) for each species and each hydrological period was obtained from Oliveira et al. (2010), who surveyed the eating habits of residents of Puruzinho Lake (Nascimento et al. 2022). The average daily intake rate of all the fish species consumed by the riverine population is 406 g·person⁻¹·day⁻¹. The mean daily intake rate by the population, considering only the four analyzed species, is 40.4 g·person⁻¹·day⁻¹ (Supplementary Material 2).

Statistical analyses

Statistical analyses were performed in the R program (R Core Team 2022). Two-way ANOVA (aov function, base package, R Core Team 2022) was carried out to evaluate the effect of hydrological periods, eating habits, and the interaction between these two variables on Pb concentrations.

Pb variations over hydrological periods for the four species were evaluated using quadratic regressions (lm function, base package, R Core Team 2022), from which trend lines were extracted. In addition, linear regressions were performed (lm function, base package, R Core Team 2022) between Pb concentrations and stable isotope data in order to assess the association between these variables. In the regression analyses, the Pb-isotope distribution is shown using ellipses (data.ellipse function, car package; Fox and Weisberg 2019), constructed at 1 standard deviation from the centroid (68% confidence interval). Linear regressions were also carried out between Pb concentration and biometric variables (total length and weight; Supplementary Material 3).

When necessary, the data were transformed using a maximum likelihood function (boxcox function, MASS package; Venables and Ripley 2002) in order to meet the assumptions of ANOVA and regressions (linearity, normality, and homoscedasticity of residuals). The ANOVA and regressions were validated using diagnostic plots (Altman and Krzywinski 2016).

Fulton's condition factor (K) was calculated as a ratio of fish weight (g) by the cube of their total length (cm) multiplied by 100 (Supplementary Material 4; Ricker 1975; Nash

et al. 2006) to assess whether the Pb concentrations found in the fish would affect their health status (e.g., $K = 1$ being a fish in perfect health, $K < 1$ indicates a “slim” fish, and $K > 1$ a “fat fish”; Ricker 1975; Nash et al. 2006; Vries et al. 2020), but we found no significant relationship between the variables (Supplementary Material 5).

The assessment of risk of Pb ingestion through fish ingestion was carried out using empirical combinatorial analysis (Monte Carlo; expand.grid function; base package; Khitalishvili 2016) with fish ingestion and Pb concentration data, which generated all possible scenarios among the aforementioned variables, incorporating the variability of both in the final result.

In all applicable cases, an a priori type I error of 5% ($\alpha = 0.05$) was assumed.

Results

The variation of Pb concentration along the hydrological periods was similar among the analyzed species (ANOVA, interaction term; $p = 0.14$). The carnivorous, herbivorous, and detritivorous fish showed an increase in Pb concentrations

during the flood season (rising and high water) followed by a decrease in concentrations during the dry season (falling and low water; Fig. 2). In contrast, the piscivorous fish showed no relevant Pb variations over the hydrological periods. However, it exceeded the maximum tolerance limit for Pb established by the Brazilian National Sanitary Surveillance Agency ($0.3 \mu\text{g}\cdot\text{g}^{-1}$; ANVISA 2021) in all the hydrological periods, with the highest median of the study being found during the rising water period (0.48 ± 0.18 ; Fig. 2).

A gradual increase in Pb concentrations was observed with increasing trophic level ($\delta^{15}\text{N}$), evidencing the occurrence of Pb biomagnification along the trophic web (Fig. 3A). Although a significant relationship between Pb concentrations and $\delta^{13}\text{C}$ was not observed, it was possible to observe that the food sources for *M. duriventre* were 10% higher compared to those of the other species, which showed a great overlap in their values (Fig. 3B).

The risk assessment of Pb ingestion indicated that consumption of the herbivorous species during the high water period exceeded the provisional safe limit established by the Food and Drug Administration of $12.5 \mu\text{g}\cdot\text{day}^{-1}$ for adults (Dolan et al. 2020; Flannery et al. 2020; Fig. 4). Although the Pb

Fig. 2 Pb concentrations in *Cichla pleiozona*, *Mylossoma duriventre*, *Prochilodus nigricans*, and *Serrasalmus rhombeus* in the four hydrological periods of the Brazilian Amazon. The red dashed line indicates the maximum tolerance limit value for Pb in fish (ANVISA 2013). The solid lines indicate the main trends of the medians over the hydrological periods and were extracted from quadratic regressions. The distances between the y-axis values were log-transformed to optimize data visualization

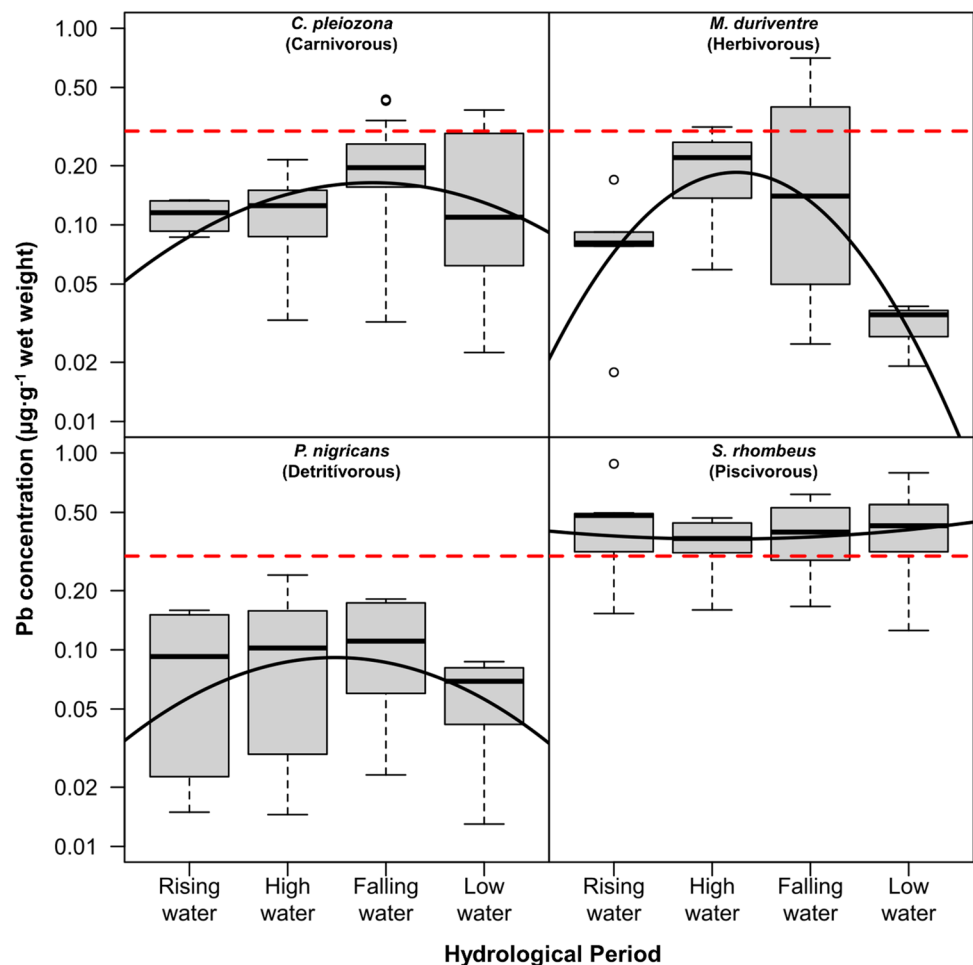
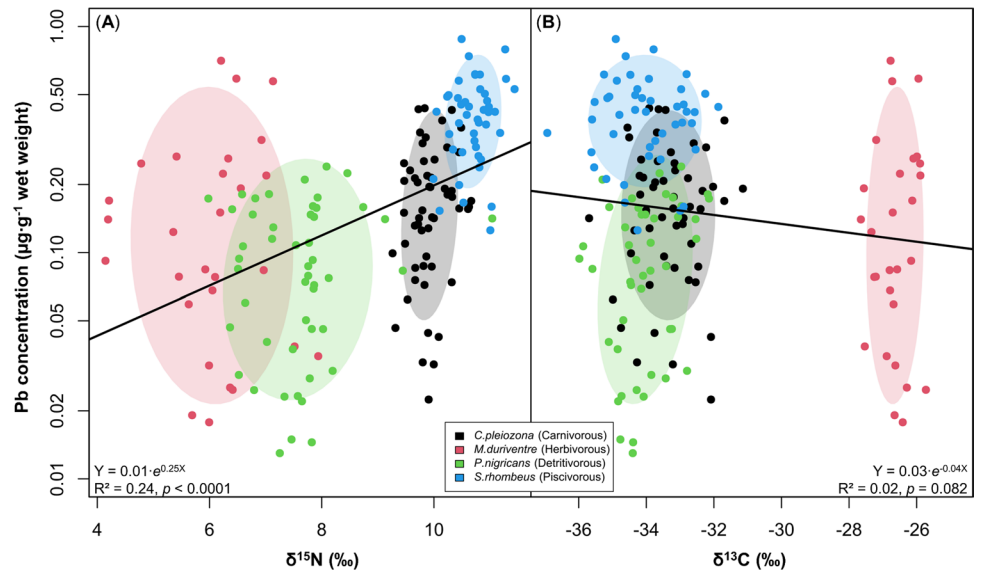


Fig. 3 Relationships between isotopic signatures of **A** nitrogen ($\delta^{15}\text{N}$) and **B** carbon ($\delta^{13}\text{C}$) and Pb concentrations in the four fish species analyzed. Ellipses were constructed at 1 standard deviation from their centroids (68% confidence interval). Regression statistics (equation, R^2 , and p -value) are within each graph. The distances between the y-axis values were log-transformed to optimize data visualization

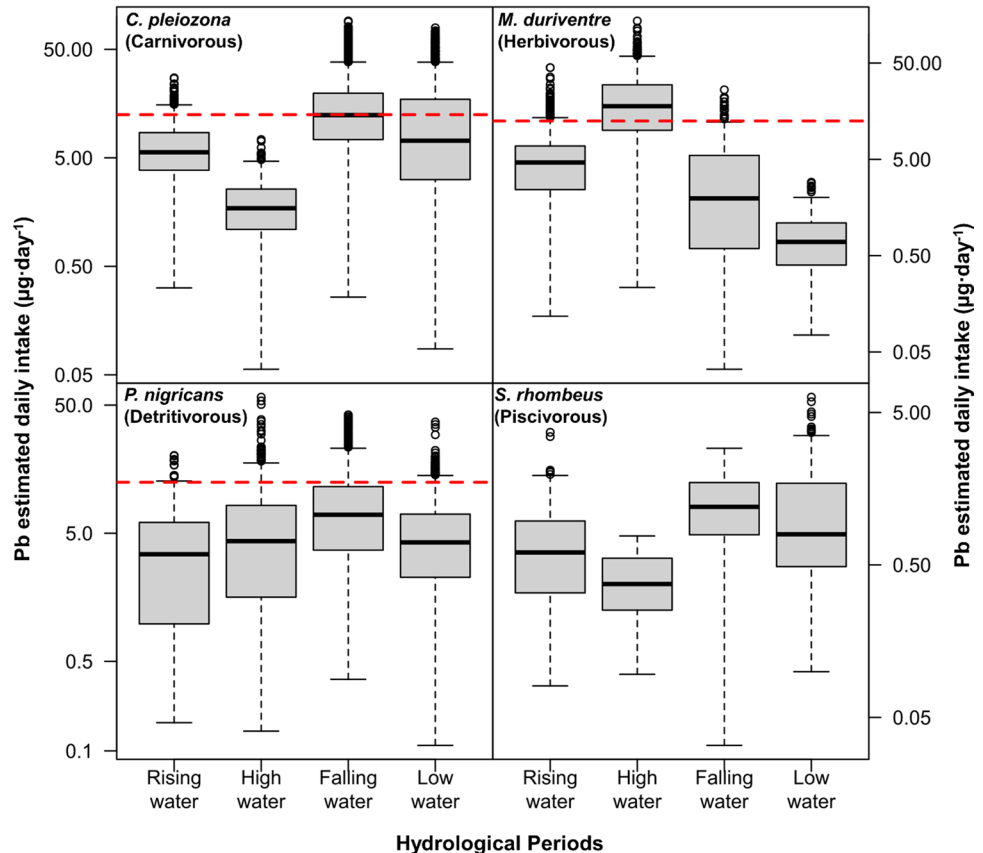


concentrations in *S. rhombeus* exceeded the maximum tolerable limit established by ANVISA (2021) (Fig. 2), the isolated consumption of this species did not lead to exposure to Pb above the safe limit by the riverine population (Fig. 4), mainly because of its low consumption (Supplementary Material 2).

Discussion

Our results show that the flood pulse directly influences the Pb concentrations observed in the carnivorous, herbivorous, and detritivorous fish. Floodplain lakes such as Puruzinho,

Fig. 4 Pb-estimated daily intake through the consumption of the studied fish species over the four hydrological periods. The dashed red line indicates the provisional safe limit of $12.5 \mu\text{g}\cdot\text{day}^{-1}$ established by the Food and Drug Administration for adults (Dolan et al. 2020; Flannery et al. 2020). The distances between the y-axis values were log-transformed to optimize visualization of the data



receive high concentrations of trace elements during flood pulses (Almeida et al. 2014; Pestana et al. 2019). This is due to the fact that the Madeira River, which invades Puruzinho Lake during flooding, is a white water river that has a high load of suspended particulate matter, one of the main geochemical supports for the transport of trace elements in aquatic ecosystems (Sioli 1968; Pestana et al. 2019). The rising and high water periods, when an increase in Pb concentrations was observed in the carnivorous, herbivorous and detritivorous fish, are precisely when Puruzinho Lake receives the highest contribution of suspended particles carried by the Madeira River. During these periods, the residence time of suspended particles rich in trace elements is longer, making them more bioavailable to the organisms ingested by the fish. With the reduction of water flow in the falling and low water periods, the particles gradually tend to settle to the bottom sediment, which may explain the decrease in the Pb concentrations in this period (Carvalho et al. 2018; Pestana et al. 2019).

These results strongly contrast with data from Nascimento et al. (2022), who analyzed the Cr variation along the hydrological periods in the same species and lake of this study due to Cr contamination via tanneries in the region. The authors identified a temporal variation of Cr concentrations in fish highly modulated by their feeding habits, which we did not observe. This makes it clear that the bioavailability of trace elements to biota in Amazon aquatic ecosystems depends heavily on the biogeochemistry of the chemical element. For example, Pb bonds strongly to the residual fraction of solids, while Cr binds to the oxidizable fraction. This means that the lake's own seasonal oxygenation change in the water column could release Cr from the sediments back into the water, while the Pb sources would be more strongly associated with the Madeira River flood pulse transporting suspended particulate matter to the lake (Jakubus 2020). Furthermore, Pb bioavailability increases in the presence of organic matter, unlike Cr, which is reduced from Cr VI (more mobile) to Cr III (less mobile). Since the lake is a black water ecosystem naturally enriched in organic matter, this can also explain the relative independence of the Pb variation in the fish in relation to their feeding habits, unlike the case of Cr (Sioli 1968; Huser et al. 2012; Nascimento et al. 2022).

These results also contrast with data from Azevedo et al. (2020), who identified a clear interaction between the hydrological periods and feeding habits modulating Hg concentrations in the same species from the same lake while studying the effects of the flood pulse and artisanal gold mining on Hg contamination in the region. Unlike Pb, it is well established in the literature that the main fish exposure to Hg is through diet, which explains this difference (Arcagni et al. 2018; Azevedo et al. 2020).

Although the ANOVA's interaction term indicated no statistical differences among slopes, the piscivorous fish

appeared not to be influenced by the flood pulse throughout the hydrological periods, unlike the other species. This may be due to the fact that *S. rhombeus* is a species with a high position in the food web ($\delta^{15}\text{N}$), which allows it to feed on prey in a relatively continuous manner throughout the hydrological periods, also explaining the relatively constant concentrations of Pb during these periods.

The fish consumption by the riverside population of Puruzinho Lake, according to Oliveira et al. (2010), is $406 \text{ g}\cdot\text{person}^{-1}\cdot\text{day}^{-1}$, contrasting with the Brazilian national average of $8.9 \text{ g}\cdot\text{person}^{-1}\cdot\text{day}^{-1}$ (Sonoda and Shirota 2012). In fact, fish consumption in the Amazon is very high, comparable to the Maldives, whose population has the highest rate of fish consumption in the world (FAO 2016), so even low levels of fish contamination can lead to a high-risk scenario.

In the high water period, the median Pb intake from the consumption of the herbivorous species ($17.82 \pm 19.68 \text{ g}\cdot\text{day}^{-1}$) exceeded the provisional limit established by the FDA (Dolan et al. 2020; Flannery et al. 2020). This is mainly due to the high consumption of this fish species during the high water period ($98.8 \text{ g}\cdot\text{day}^{-1}$; Supplementary Material 2) and means that the isolated consumption of this fish can lead to health problems related to Pb contamination among the population of Puruzinho Lake, such as neurological, hematological, and renal problems (Moreira and Moreira 2004; Schifer et al. 2005). Two aggravating factors should be highlighted in this risk analysis. First, this analysis is an oversimplification of the actual eating habits of the community of Puruzinho Lake. To perform this analysis, we evaluated the isolated consumption of each species in each hydrological period, assuming that only one of them is consumed at a time. In practice, fish consumption varies among meals on the same day, making the Pb intake through the consumption of the species consumed in a single day cumulative. This means that the actual (cumulative) risk could be orders of magnitude higher than our estimates, which raises concerns. Furthermore, our data indicate moderate evidence of Pb biomagnification along the lake food chain ($R^2=0.24$, $p<0.0001$) but higher compared to other studies ($R^2=0.06$, $p=0.019$; Jiang et al. 2018), which makes consumption of predatory fish the worst case risk scenario. Pb biomagnification is a controversial topic in the literature, as some studies show negative associations with Pb exposure in controlled experiments (Cardwell et al. 2013) and in field observations (Liu et al. 2018; Souza-Araujo et al. 2022). However, our data are in agreement with the findings of other authors in highly industrialized environments (Yi et al. 2017).

Our results of Pb intake are concerning, especially regarding the herbivorous species. Since this species consumes mostly plants (as reflected in its $\delta^{13}\text{C}$, 10‰ different from the other species on average), it is possible to infer that the Pb in the lake is bioavailable for absorption by primary

producers, which transfer the Pb to herbivores. The observed Pb intake values are in the range reported in other industrially polluted areas. Bassey and Chukwu (2019) found Pb intake between 3.9 and 8.3 $\mu\text{g}\cdot\text{day}^{-1}$ through the consumption of a demersal detritivorous species from two lagoons in southwestern Nigeria. The authors stated that the high Pb concentrations found in the fish were due to wastewater discharges from local textile factories, printing cartridge waste, and other industrial effluents. Differently, Jiang et al. (2018) reported a mean Pb intake of 1.9 $\mu\text{g}\cdot\text{day}^{-1}$ while studying 12 fish species in the second largest freshwater lake in China. While the authors stated that the area is one of the most industrialized in China, trace element concentrations in fish, including Pb, showed that the species had low levels of contaminants, which reflected the low estimated daily Pb intake.

Conclusion

Pb concentrations in herbivorous, detritivorous, and carnivorous species varied similarly according to hydrological periods, with the highest concentrations being observed in the flood season (rising and high water periods). This variation is probably related to the influence of the Madeira River water, which transports high loads of suspended particles with high adsorption capacity of metals. The piscivorous fish presented relatively constant Pb concentrations throughout the four hydrological periods, suggesting that they have a relatively stable diet throughout the year. Because of that, we can only partially refute our main hypothesis.

The consumption of the herbivorous species during the high water period has the potential to pose risks to the health of the riverside population of Puruzinho Lake. Given the moderate evidence of Pb biomagnification in the food chain, attention should also be paid to the consumption of predatory fish. In addition, it is worth noting that the data presented concern only four species of fish consumed by the community of Puruzinho Lake. Considering other species and their simultaneous ingestion on the same day, the risk scenario may be much greater than we estimated.

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Author contribution Sophia Menezes de Azevedo: writing (original draft and review and editing); Luiza Silva do Nascimento: writing (review and editing); Layra de Oliveira Silva: writing (review and editing); Marcelo Gomes de Almeida: validation and methodology; Lucas Silva Azevedo: writing (review and editing); Wendel Dias Constantino: writing (review and editing); Wanderley Rodrigues Bastos: resources and funding acquisition; Inácio Abreu Pestana: conceptualization, project administration, supervision, and writing (review and editing).

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Data availability The data that support the findings of this study are available from the corresponding author, I.A. Pestana, upon reasonable request.

Declarations

Consent to publish All the authors agreed with the content of this manuscript and gave explicit consent for submission.

Competing interests The authors declare no competing interests.

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