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RESEARCH ARTICLE

Risk of exposure to Hg and pesticides residues in a traditional fishing community in the Amazon: a probabilistic approach based on dietary pattern

Lucas Silva Azevedo[1] · **Inácio Abreu Pestana**[1] · **Luiza Nascimento**[1] · **Ronaldo Cavalcante Oliveira**[2] · **Wanderley Rodrigues Bastos**[2] · **Ana Paula Madeira di Beneditto**[1]

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Abstract

Exposure to mercury (Hg) and pesticides (*o.p'*DDT, *p.p'*DDT, *o.p'*DDE, and *p.p'*DDE) in the Amazon through eating fish is of concern due to the large participation of this food in the diet of traditional fishing communities. The aim of this study was to evaluate the estimated daily intake (EDI) and the incremental lifetime cancer risk associated with Hg and *o.p'*DDT, *p.p'*DDT, *o.p'*DDE, and *p.p'*DDE in an Amazonian community. The results showed that for Hg, the EDI from carnivorous and detritivorous fish had the highest values, while for pesticides, the EDI from detritivorous fish intake had the highest value. The incremental lifetime cancer risk was below the permitted limit. A recommendation for controlling the high risk of exposure includes the reduction of detritivorous fish ingestion and/or replacement with herbivorous fish, which had lower EDI. We highlight the importance of investigating the human dietary patterns when estimating risk of exposure to Hg and pesticides.

Keywords Risk assessment · Probabilistic · Cancer · Monte Carlo simulation · Environmental pollution · Fish intake

Introduction

Fish consumption is linked to health benefits such as reduction of coronary disease risk and improvement of neurological development (Hellberg et al. 2012; Torrissen and Onozaka 2017). Moreover, fish intake provides proteins, omega-3 fats, vitamin B_{12}, vitamin D, iron, and other minerals like selenium, zinc and iodine (WHO/FAO 2011; Hicks et al. 2019; Maciel et al. 2019). Due to these benefits, fish is considered part of a "healthy eating pattern" by the joint committee of the World Health Organization and United Nations Food and Agriculture Organization (WHO/FAO 2011).

In Brazil, fish consumption is heterogeneous among the country's five official regions (North, Northeast, Midwest, South, and Southeast): The mean fish intake per capita in the North region is 45.0 g day^{-1}, while in Southeast, it is only 6.1 g day^{-1} (IBGE 2010). Although the aforementioned mean values represent the general fish intake rates of the North and Southeast, there are some specific population segments in these regions with drastically different intake rates. The traditional "caboclo" (descendants of indigenous Brazilians and Portuguese immigrants) fishing communities in the Amazon (North region) are a good example of a population segment that differs in terms of dietary habits from the average regional values. These people rely heavily on fish as a source of animal protein, which is reflected in one the highest fish intake rates in the country (Begossi et al. 2019). For instance, in the fishing community of Monte Alegre (in the lower Amazon River basin), the fish intake rate is 366 g per capita day^{-1} (or 133.59 kg per capita year^{-1}) (Cerdeira et al. 1997), approximately 8 times higher than the average of the North region. This high fish intake is also observed in fishing communities in the Lower Solimões/Upper Amazon basin (550 g per capita day^{-1} or 182 kg per capita year^{-1}) (Bastista

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✉ Lucas Silva Azevedo
lucasazevs@pq.uenf.br

[1] Laboratório de Ciências Ambientais, Centro de Biociências E Biotecnologia, Universidade Estadual Do Norte Fluminense Darcy Ribeiro, Campos dos Goytacazes, Rio de Janeiro, RJ 28013-602, Brazil

[2] Laboratório de Biogeoquímica Ambiental, Universidade Federal de Rondônia, Porto Velho, Rondônia, RO CEP: 76815-800, Brazil

et al. 1998) and from the Madeira River basin (243 g per capita day^{-1} or 88.7 kg per capita year^{-1}) (Boischio and Henshel 2000). In general, fish intake in the Amazon region is higher or very similar to the intake in Iceland (92 kg per capita year^{-1}), which has the second highest fish consumption in the world (FAO, 2021).

Although fish intake provides many health benefits, there is still a risk for consumers due to the high concentration of contaminants like mercury (Hg) and organochlorine pesticides (OCPs). Hg is a neurotoxic metal that can be easily absorbed and accumulated in fish tissues. Consumption of fish meat with high levels of Hg can cause serious health problems and, in some cases, death (Genchi et al. 2017; Vasconcelos et al. 2018; Lacerda et al. 2020). The most notorious incident of Hg poisoning through fish intake happened in Minamata, Japan, in 1956, when thousands of people were exposed. Harada (1995) reported that the most common symptoms of "Minamata disease" were sensory disturbances, ataxia, dysarthria, constriction of the visual field, auditory disturbances, and tremors. A total of 1,043 people died from this disease from 1959 to 1995 (Harada 1995). Hg poisoning continues to pose a risk to the population even 62 years after the Minamata incident (Yorifuji et al. 2017).

OCPs are contaminants that can be easily dispersed in the environment and have long half-lives, high toxicity, and potential carcinogenicity (Androutsopoulos et al. 2013; Yadav et al. 2015; Raanan et al. 2016; Attaullah et al. 2018; Mekonen et al. 2021). OCPs are used in agriculture to control weeds and insect pests, including those that act as disease vectors (Hafeez et al. 2020). From 1939 to 1970, dichlorodiphenyltrichloroethane (DDT) was one of the most commonly used OCPs to control vectors of malaria, yellow fever and leishmaniasis. Particular attention should be given to the Amazon, where DDT was extensively used, since malaria is considered an endemic disease in the region (Barata 1995). Saldanha et al. (2010) and Mendes et al. (2016) observed concentrations of DDT and other metabolites, e.g., dichlorodiphenyldichloroethylene (DDE) and dichlorodiphenyldichloroethane (DDD), in fish from Puruzinho Lake and the Tapajós River, respectively, demonstrating that even after the DDT ban in 1998, these pesticides still can accumulate in the biota.

Considering the toxicity and biomagnification potential of Hg and DDT, it is crucial to estimate the risk that these contaminants pose to consumers. Risk assessments are used to characterize the magnitude of health risk to humans from chemical contaminants (USEPA 2011a). There are two methods to estimate risk: deterministic and probabilistic. The deterministic method is suitable to screening-level assessments due to its use of single point value and simple modeling, which means that the results are appropriate to compare sites and prioritize or rule out exposure pathways (USEPA 2011a). A limitation of the deterministic method is that the uncertainty inherent to contaminant concentration and food intake cannot be incorporated in the calculations, which can lead to unrealistic assessments. In contrast, the probabilistic approach is suitable for refined assessments when more realistic and better characterization of uncertainty and variability are required (USEPA 2011a). Both methods have strong and weak points, so choosing one or another depends on the aim of the study and data quality.

The aim of this study was to provide a robust diagnosis of exposure to Hg and pesticides (*o.p'*DDT, *p.p'*DDT, *o.p'*DDE, and *p.p'*DDE) through fish intake, using the probabilistic approach, in a very common type of community in the Amazon, a "caboclo" fishing community.

Material and methods

Study site

Puruzinho Lake

Puruzinho Lake is located in the municipality of Humaitá, Amazon state (63°6′0″W; 7°24′0″S). It is floodplain lake with black water (i.e., acid pH and high concentration of dissolved organic matter), connected to the Madeira River through an 8 km channel. The Puruzinho Lake community has only 20 households and approximately 170 people (Oliveira et al. 2010). The region is relatively isolated and pristine, and the closest city is 3 h away by boat. Besides fish (the main source of protein), the diet is composed mainly of cultivated cassava (*Manihot esculenta*) and foods collected in the surrounding forest, like Brazil nuts (*Bertholletia excelsa*) and the fruits tucumã (*Astrocaryum aculeatum*), açaí (*Euterpe oleracea*), patoá (*Oenocarpus bataua*), and abacaba (*Oenocarpus bacaba*) (Oliveira et al. 2010), although some families breed pigs and chickens.

Database

Hg and pesticides

Hg and *o.p'*DDT, *p.p'*DDT, *o.p'*DDE, and *p.p'*DDE concentrations in fish from Puruzinho Lake were obtained from the previous studies of Azevedo et al. (2020) and Saldanha et al. (2010), respectively. The fish species were pooled into four guilds, carnivorous, detritivorous, herbivorous, and omnivorous, according to the classification given by Azevedo et al. (2020) and Saldanha et al. (2010). The number of samples, the mean, and the standard deviation of Hg and pesticide concentrations in the fish guilds are described in Supplementary Materials 1 and 2, respectively.

Fish intake and body weight

Raw data about fish intake were obtained from Oliveira et al. (2010). These authors interviewed 16 families in living on the shores of Puruzinho Lake from August 2006 to January 2007. Each family received a digital scale to weigh any fish consumed during the day. Additionally, the families received a spreadsheet to register fish weight and the common name of the consumed species. For example, if a family consumed a tucunaré (*Cichla pleiozona*) and a pacu (*Mylossoma duriventre*) on day 01/08, they would weigh the fish meat before cooking and record the value on the spreadsheet. The database available in Oliveira et al. (2010) comprises in detail the daily dietary pattern of the Puruzinho community during 183 consecutive days (or 6 months).

The fish intake (g person^{-1}) was calculated by dividing the total weight of fish consumed (g) in a day by the number of members of the family. To calculate the mean fish meal intake, we pooled the species into each guild and one group with all guilds (Table 1).

Risk assessment design

The risk assessment is based on three metrics: the estimated daily intake (EDI), the lifetime average daily doses (LADD), and the incremental lifetime cancer risk (ILCR). Each of these metrics was calculated based on contaminant concentration pooled in fish guilds (Table 2). The LADD and ILCR calculation is based solely on *p.p'*DDT concentrations because this is the only compound with carcinogenic proprieties (IRIS 1998) (Table 2).

Considering the inherent differences in weight, food intake rate, and lifetime exposure, which can influence the risk assessment metrics, the population living around Puruzinho Lake was pooled into three age groups: teenagers (12–17 years), adults (18–64 years), and elderly (65 to < 75 years) (Table 2). Therefore, EDI, LADD and ILCR were calculated for the three age groups (Table 2).

EDI estimated daily intake, *LADD* lifetime average daily dose, *ILCR* incremental lifetime cancer risk.

Data analysis

Estimated daily intake (EDI)

The EDI (mg kg day^{-1} for Hg; ng kg day^{-1} for pesticides) is calculated based on Ihedioha and Okoye (2013):

$$EDI = \frac{C.IR}{BW}$$

where,

C is the contaminant concentration in mg kg^{-1} wet weight.

Table 1 Mean fish intake (g person^{-1}) of Puruzinho community

		Carnivorous	Detritivorous	Herbivorous	Omnivorous	All guilds
Fish intake	Mean	78.56	121.39	58.43	45.15	75.88
	SD	157.30	179.84	127.80	119.13	150.76

Table 2 Risk assessment design, where "x" represents which analysis was considered

		Age groups: 12–17 years; 18–64 years; 65 to < 75 years				
Metrics	Fish guilds	Hg	*o.p'*DDT	*p.p'*DDT	*o.p'*DDE	*p.p'*DDE
EDI	Carnivorous	X	X	X	X	X
	Detritivorous	X	X	X	X	X
	Herbivorous	X	X	X	X	X
	Omnivorous	X	X	X	X	X
	All guilds	X	X	X	X	X
LADD	Carnivorous			X		
	Detritivorous			X		
	Herbivorous			X		
	Omnivorous			X		
	All guilds			X		
ILCR	Carnivorous			X		
	Detritivorous			X		
	Herbivorous			X		
	Omnivorous			X		
	All guilds			X		

IR is the intake ratio of fish in g person^{-1} (Table 1).
BW is the body weight in kg (IBGE 2010; Supplementary Material 3).

Lifetime average daily dose and incremental lifetime cancer risk

The LADD and ILCR are calculated based on USEPA (2011) solely for *p.p*'DDT:

$$LADD = \frac{C.IR.ED.EF}{BW.ATe}$$

$$ILCR = LADD.CSF$$

where,

C is the contaminant concentration in mg g^{-1} wet weight.
IR is the intake ratio of fish in g person^{-1} (Table 1).
ED is the exposure duration in years (5, 46, and 56.8 years for teenagers, adults, and elderly).
EF is the exposure frequency, representing how many days in the year the person ingests a certain food: carnivorous (102 days), omnivorous (68 days), herbivorous (88 days), and detritivorous (158 days) (Oliveira et al. 2010).
BW is the body weight in kg.
ATe is the mean life expectancy in days (74.8 years or 27,302 days) (IBGE 2020).
CSF is the cancer slope risk factor for $p.p'DDT$ ($3.4 \bullet 10^{-1}$ mg kg day^{-1}) (IRIS 1998).

The ILCR is defined by USEPA (2001) as the maximum theoretical number of cancer cases that are possible to occur due to contaminant exposure. The value of ≤ 1 cancer cases per 100,000 people (10^{-5}) is deemed to be "essentially negligible" (Heath Canada 2010). Oral exposure to *p.p*'DDT is related to hepatic tumors in humans (USEPA 2021).

Simulations

The descriptive statistics in this study (median, interquartile range (IQR) and 95th percentile) were calculated using the R program (R Core Team 2021) through empirical combinatorial analyses (expand.grid function; base package; Monte Carlo method, Khitalishvili 2016) so that the errors associated with contaminant concentration, fish consumption, and body weight were correctly propagated in the final result. The number of combinations performed did not exceed X•Y•Z, with X, Y, and Z being the values of contaminant concentration, fish consumption, and body weight.

Since we did not have access to raw OCP concentrations and body weight, we assumed a normal distribution of these variables and used the mean, standard deviation, and sample size reported by Saldanha et al. (2010) to create a dataset (rnorm function, base package, R Core Team 2021) with the same mentioned statistical characteristics.

Results

Estimated daily intake—Hg

Hg EDI was highest for the carnivorous guild and lowest for the herbivorous guild which reflects the higher Hg concentration in predatory fish (Table 3). The EDI of the detritivorous guild was higher than the omnivorous guild (Table 3).

Table 3 Estimated daily intake of Hg (mg day^{-1} kg^{-1}) and pesticides (ng day^{-1} kg^{-1}). Values are median and the interquartile interval

Fish guild	Pollutants		
	Teenagers	Adults	Elderly
	Hg		
Carnivorous	1.36 ± 1.48	1.04 ± 1.11	1.11 ± 1.17
Detritivorous	0.44 ± 0.48	0.33 ± 0.37	0.33 ± 0.36
Herbivorous	0.08 ± 0.13	0.06 ± 0.10	0.07 ± 0.11
Omnivorous	0.23 ± 0.37	0.18 ± 0.28	0.18 ± 0.28
All guilds	2.46 ± 1.73	1.89 ± 1.33	1.98 ± 1.38
	o.p'DDT		
Carnivorous	0.30 ± 0.68	0.24 ± 0.52	0.26 ± 0.54
Detritivorous	0.60 ± 1.21	0.47 ± 0.93	0.48 ± 0.93
Herbivorous	0.16 ± 0.25	0.13 ± 0.18	0.13 ± 0.20
Omnivorous	0.08 ± 0.50	0.06 ± 0.37	0.06 ± 0.40
All guilds	1.40 ± 1.85	1.10 ± 1.41	1.10 ± 1.43
	p.p'DDT		
Carnivorous	0.67 ± 0.92	0.52 ± 0.66	0.56 ± 0.72
Detritivorous	1.33 ± 2.37	1.04 ± 1.91	1.10 ± 2.00
Herbivorous	0.40 ± 0.63	0.31 ± 0.46	0.34 ± 0.52
Omnivorous	0.33 ± 0.78	0.26 ± 0.63	0.27 ± 0.62
All guilds	3.55 ± 3.24	2.74 ± 2.52	2.90 ± 2.60
	o.p'DDE		
Carnivorous	0.66 ± 1.72	0.52 ± 1.35	0.56 ± 1.37
Detritivorous	1.10 ± 4.78	0.80 ± 3.60	0.82 ± 3.72
Herbivorous	0.27 ± 1.00	0.21 ± 0.75	0.23 ± 0.82
Omnivorous	0.66 ± 2.55	0.55 ± 2.13	0.55 ± 2.10
All guilds	3.48 ± 7.20	2.72 ± 5.52	2.76 ± 5.60
	p.p'DDE		
Carnivorous	0.11 ± 0.75	0.08 ± 0.58	0.10 ± 0.60
Detritivorous	1.04 ± 3.48	0.72 ± 2.50	0.72 ± 2.50
Herbivorous	0.20 ± 0.37	0.15 ± 0.26	0.16 ± 0.30
Omnivorous	0.41 ± 1.04	0.32 ± 0.78	0.34 ± 0.82
All guilds	1.93 ± 4.10	1.41 ± 3.00	1.43 ± 3.00

This result is related to the higher intake (g person^{-1}) of detritivorous fish in comparison with omnivorous and herbivorous fish (Table 1). The higher EDI of detritivorous in comparison with omnivorous fish highlights the relevance of proper characterization of food intake when conducting risk assessment, because this variable can in some cases offset the low pollutant concentration and increase the risk.

Considering all fish guilds, the EDI was slightly higher for teenagers in comparison with adults and elderly (Table 3).

The 95th percentile of the EDI probability distribution can be used to infer the worst-case scenario of a contaminant exposure (Table 4). In this scenario, Hg EDI from herbivorous fish, for all age groups, showed a value 6.8-fold higher than the median presented in Table 3, which is the highest increase in EDI in comparison with the other fish guilds. The 95th Hg EDIs from omnivorous, carnivorous, detritivorous, and all fish guilds were 5.2, 3.3, 3.2, and 2.3 times higher than the median, respectively (Table 4).

Table 4 The 95th percentile of the estimated daily intake of Hg (mg day^{-1} kg^{-1}) and pesticides (ng day^{-1} kg^{-1})

Fish Guild	Hg		
	Teenagers	Adults	Elderly
Carnivorous	4.76	3.30	3.58
Detritivorous	1.47	1.05	1.10
Herbivorous	0.53	0.44	0.47
Omnivorous	1.25	0.90	0.95
All guilds	6.13	4.30	4.63
	o.p'DDT		
Carnivorous	2.00	1.40	1.50
Detritivorous	3.45	2.72	2.67
Herbivorous	0.70	0.50	0.52
Omnivorous	0.78	0.56	0.61
All guilds	4.80	3.70	3.65
	p.p'DDT		
Carnivorous	2.65	1.85	2.04
Detritivorous	6.80	5.10	5.10
Herbivorous	1.63	1.21	1.31
Omnivorous	2.61	1.93	2.02
All guilds	9.66	7.11	7.32
	o.p'DDE		
Carnivorous	3.66	3.00	3.03
Detritivorous	12.32	8.13	9.01
Herbivorous	2.17	1.61	1.63
Omnivorous	5.50	4.20	4.52
All guilds	15.92	11.26	12.20
	p.p'DDE		
Carnivorous	1.40	1.05	1.13
Detritivorous	7.05	5.17	5.33
Herbivorous	0.70	0.52	0.60
Omnivorous	2.02	1.60	1.56
All guilds	8.25	6.10	6.28

Estimated daily intake—pesticides

The EDI of pesticides showed the following patterns: *o.p*'DDT and *p.p*'DDT (detritivorous > carnivorous > herbivorous > omnivorous); *o.p'DDE* (detritivorous > omnivorous > carnivorous > herbivorous); and *p.p*'DDE (detritivorous > omnivorous > herbivorous > carnivorous) (Table 3). These results show that EDI of the four pesticides was higher in the detritivorous guild. The fish intake ratio of the detritivorous guild was one order of magnitude higher than the other fish guilds (Table 1), which can further increase the EDI value. Similar to the EDI of Hg, the EDI of pesticides from all fish guilds was higher in the teenage age group in comparison with adult and elderly groups. The 95th percentile of *o.p*'DDT and *p.p*'DDT EDI of omnivorous fish showed values 9 and 7 times higher than the median, respectively; for *o.p*'DDE, the EDI of detritivorous fish showed a value 11 times higher than the median; and for *p.p*'DDT, the EDI of carnivorous fish showed a value 12 times higher than the median (Table 4).

Lifetime average daily dose and cancer risk

The LADD of *p.p*'DDT was higher for the detritivorous guild, followed by carnivorous, herbivorous, and omnivorous (Table 4). The higher value of LADD for detritivorous fish is consistent with the EDI of *p.p*'DDT presented in Sect. 3.2. Although both metrics (EDI and LADD) followed similar patterns regarding which guild showed the highest value, the results among age groups were not similar between LADD and EDI. For LADD, the elderly group showed the highest values (Table 4). This result is due to the inclusion of exposure frequency (in days) and exposure duration (in years) in the LADD calculation. These variables contributed to the higher LADD values observed in the elderly age group, since this group had been exposed to contaminants longer than teenagers and adults.

In general, the ILCR values were lower than the acceptable cancer cases established by USEPA (2001) (Table 4). Lower values of ILCR in teenagers are expected due to their young age and low exposure time to *p.p*'DDT. For the adult and elderly age groups, the values were also lower than the acceptable limit of USEPA (2001). Similar to the EDI and LADD, the ILCR for adults and elderly associated with detritivorous fish ingestion was the highest among the four guilds (Table 5).

Table 5 Lifetime average daily dose and incremental lifetime cancer risk (both •10^{-5}) for *p.p'*DDT

Guilds	Lifetime average daily dose			Incremental lifetime cancer risk		
	Teenagers	Adults	Elderly	Teenagers	Adults	Elderly
Carnivorous	0.015 ± 0.018	0.090 ± 0.117	0.114 ± 0.147	0.012 ± 0.006	0.030 ± 0.036	0.040 ± 0.051
Detritivorous	0.039 ± 0.069	0.282 ± 0.501	0.360 ± 0.648	0.012 ± 0.024	0.093 ± 0.171	0.123 ± 0.222
Herbivorous	0.006 ± 0.009	0.048 ± 0.066	0.201 ± 0.360	0.003 ± 0.003	0.015 ± 0.024	0.070 ± 0.123
Omnivorous	0.003 ± 0.009	0.030 ± 0.066	0.040 ± 0.093	0.003 ± 0.003	0.012 ± 0.024	0.012 ± 0.030
All guilds	0.075 ± 0.078	0.537 ± 0.558	0.924 ± 0.873	0.024 ± 0.027	0.180 ± 0.189	0.315 ± 0.294

Discussion

Hg exposure

The results of Hg EDI showed that carnivorous fish ingestion is the main risk factor of exposure to this toxic metal. This result can be explained by two factors: (1) Hg biomagnification and (2) exposure frequency to Hg through carnivorous fish intake. It is well established that the concentration of organic Hg increases along the food web due to its chemical properties (e.g., strong bonding to thiol protein groups, low excretion rates); thus, the organisms at the top (i.e., carnivorous/piscivorous) often show higher levels of this contaminants in the muscle tissue. This was the case in Puruzinho Lake, where carnivorous/piscivorous fish showed higher Hg concentration in comparison with detritivorous, omnivorous, and herbivorous fish (Azevedo et al. 2020, 2021). The exposure frequency (EF) to Hg through carnivorous fish intake was 102 days, in other words, the population studied eat carnivorous fish on average 102 days a year, which is the second highest EF value. The higher Hg concentration and EF value contribute to make carnivorous fish the food type that contributes the most to the risk of exposure.

The EDI of Hg from detritivorous fish intake was almost two times higher than the EDI of Hg from omnivorous fish intake. This was an unexpected result, since omnivorous fish of Puruzinho Lake showed higher levels of Hg in comparison with detritivorous fish (Azevedo et al. 2020). The main factor contributing to this result was the higher EF of detritivorous fish, 158 days, against 68 days for the omnivorous. Additionally, detritivorous fish intake was almost 2.5 times higher than omnivorous fish intake (Table 1). These results highlight that the dietary preferences of a population cannot be overlooked when conducting and planning contaminant risk assessment. There is extensive literature about Hg measurement in fish from the Amazon region (e.g., Castro et al. 2016; Azevedo et al. 2020; Hacon et al. 2020; Silva and Lima 2020), providing crucial information for planning risk assessment. However, detailed characterization of dietary habits of traditional communities is still sparse, and the available data, although relevant, are not adequate for EF or IR calculation. It is understandable that a comprehensive characterization of dietary habits is difficult in remote regions, but research groups interested in evaluating Hg exposure though fish intake should concentrate their efforts and resources on detailed characterization of dietary habits. Questionnaires with photographs showing previously weighed food were a viable option used by Azevedo et al. (2018) to study arsenic exposure through beef intake in Campos dos Goytacazes, Rio de Janeiro state, Southeast Brazil.

Comparisons with other similar studies showed that all the Hg EDI values presented in Tables 3 and 4 were lower than in Japan (Watanabe et al. 2021) and Canada (Juric et al. 2017). Comparing risk assessment studies should be done with care due to differences in methods. To the best of our knowledge, this is the first study in the Amazon region to use a probabilistic approach combined with a detailed dietary survey for risk assessment.

In order to make comparisons with the results of this study, the provisional tolerable weekly intake (PTWI) of 4 mg kg week^{-1} (JECFA 2003; WHO 2004) had to be converted to mg kg day^{-1} by dividing the number by 7, resulting in 0.6 mg kg day^{-1}. The median Hg EDI from carnivorous fish and all guilds were 2 and 4 times higher than the PTWI, respectively, which suggests a higher exposure risk to the Puruzinho Lake population. The scenario is even worse when the PTWI is compared with the 95th of Hg EDI, because only the EDI from herbivorous fish showed values lower than the PTWI.

Pesticide exposure

Although Puruzinho Lake is relatively well preserved and DDT pesticides were banished many years ago in Brazil, the risk of exposure to these contaminants through fish intake still exists. It is natural to presume that fish would be exposed to DDT and its metabolites, since these contaminants are ubiquitous in the environment and have biomagnification potential. In this study, it was possible to identify which fish guild contributed the most to the EDI and ILCR: the detritivorous guild. The fact that the consumption of detritivorous fish increases the risk of exposure to DDT and metabolites is worrying due to the preference for detritivorous species among consumers in general.

Detritivorous fish like *Prochilodus nigricans* is the preferred species for consumption in other traditional communities in the Amazon region (Cerdeira et al. 1997). In fact, Teles (2008) considered *P. nigricans* to be one of the key species for commercial and subsistence fishing. Other detritivorous species, like *Semaprochilodus insignis*, are also important to fisheries. In the Port of Manacapuru in Amazonas state, *S. insignis* and *P. nigricans* were the first and the third most landed fish, respectively, representing 23.7% and 17.7% of the total catch (Matos et al. 2018). In 2020, the Institute for Sustainable Agrarian and Forest Development of the State of Amazonas (IDAM) reported that species of the genus *Semaprochilodus* are the most consumed in the state (IDAM 2020). It is still unknown if the detritivorous fish ingestion among the general population of the Amazon region (i.e., excluding traditional fishing communities) also contributes to a higher risk of exposure to DDT and metabolites, but based on the consumers' strong preference for fish species from this guild, it is safe to assume that the risk of exposure to pesticides through detritivorous fish intake cannot be overlooked.

Pesticide cancer risk

The ILCR values associated with *p.p'*DDT exposure through fish intake were very low. This result is similar to that reported by Kasza et al. (2020), who also observed a low ILCR associated with *p*.p'DDT intake through freshwater fish intake. The ILCR values of *p.p'*DDT associated with other types of food intake, like cow's milk (Chandrakar et al. 2020), rice (Almutairi et al. 2021) and seafood (Tsygankov et al. 2019), were also low. The result of ILCR presented in this paper is similar to the ILCR associated with ingestion of other contaminants (Azevedo et al. 2018). The ILCR from inorganic arsenic ingestion through meat intake estimated for Campos dos Goytacazes, in Southeast Brazil (Azevedo et al. 2018), estimated by a similar method, was only one case in 10,000 of bladder/lung cancer in adults older than 21 years old.

It is important to note that the low ILCR associated with *p.p'*DDT ingestion in the Puruzinho community does not mean the scientific community should overlook the risk of *p.p'*DDT exposure. In this study, the ILCR was estimated for fish intake, so other food types were not considered. A total dietary study should be the next step in evaluating the risk of exposure to pesticides in traditional Amazonian fishing communities. To accomplish this goal of a total diet study, two limitations must be addressed: (1) the lack of a detailed diet characterization and (2) the scarce information about pesticide concentrations in food items consumed in traditional fishing communities. The first limitation can be overcome by selecting one traditional community and interviewing the members about their diet. It is important to obtain information about the food intake in grams and how many times in a week the food is consumed. After the diet characterization, the food should be sampled and pesticide concentrations quantified. Measuring pesticide levels after diet characterization makes exposure risk investigation more precise.

Considerations about the risk assessment

The results presented in this paper are based on Hg concentration in fish from a "black water" ecosystem. This classification indicates that Puruzinho Lake has an acid pH and high concentration of dissolved organic matter (Sioli, 1967). These conditions increase Hg methylation rate which, in turn, results in higher Hg concentrations in sediments and biota from black water ecosystems compared to other Amazonian aquatic ecosystems (e.g., white-water ecosystems, characterized by neutral pH and high concentration of particulate matter, and clear water ecosystems, characterized by very low concentration of particulate matter; Vieira et al. 2018). Due to the presumable differences in Hg concentrations among fish from the three Amazonian aquatic ecosystems (black, white, and clear water waterbodies), it is natural to assume that the risk assessment presented in this paper is restricted to populations that consumes fish from black water aquatic ecosystems. However, Puruzinho is a floodplain lake (or a "varzea" lake), which means that the lake is under a seasonal regime of inundations followed by a period of receding waters. These floodplain lakes are a very common formation widespread across the Amazon region (Affonso et al. 2015; Feitosa et al. 2019). Therefore, the presented risk assessment can be extrapolated to traditional and riverine populations that consume fish from floodplain lakes and not just from black water aquatic ecosystems.

Besides the water chemistry, the typical hydrological regime of floodplain lakes (i.e., seasonal inundations followed by receding waters) also affects Hg concentrations in fish, thus the risk of exposure to the consumers (Azevedo et al. 2020). The presented risk assessment of Hg exposure was carried out using retrieved Hg concentration data in fish from Azevedo et al. (2020). Since the aforementioned dataset comprises the four distinct hydrological periods of a floodplain cycle (i.e., rising water, high water, falling water, and low water), the probabilistic risk assessment presented integrates the variability and asymmetry of Hg concentration along the four periods.

Regarding the pesticides, to the best of the author's knowledge, there are no studies reporting how concentrations in fish fluctuates along the four hydrological periods of a floodplain cycle in Amazon. Without this information, it is not possible to assume that a pesticide concentration would be higher or lower during a specific hydrological period.

Conclusions

The results of this study call the attention to the relevance of including detailed dietary patterns in studies about human exposure to contaminants. In this regard, it was possible to confirm that the Hg EDI from carnivorous and detritivorous fish ingestion showed the highest values, while for pesticides, the EDI was highest from detritivorous fish ingestion. Both the population of the Puruzinho Lake community and the general population of the Amazon region have a high preference for detritivorous fish, which raises concern due to the higher EDI values of Hg and pesticides from ingestion of fish of this guild. Liver cancer risk associated with *p.p'*DDT ingestion through fish intake was below the limits.

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Author contribution Lucas Silva Azevedo was responsible for experimental design and wrote the paper; Inácio Abreu Pestana was responsible for the statistical analysis and participate in the experimental design; Luiza Nascimento revised the paper; Ronaldo Cavalcante de Oliveira provided the data of traditional fisher's dietary patterns; Wanderley Rodrigues Bastos was responsible for the mercury analysis of Puruzinho Lake fish samples; Ana Paula Madeira di Beneditto participated in the experimental design and revising the paper. All authors were participated in this work.

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Data Availability All relevant data are within the manuscript and available from the corresponding author upon request.

Declarations

Ethics approval This article does not contain any studies with human participants or animals performed by any of the authors.

Consent for publication All authors agree to publish.

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