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Original Article

Metal concentrations in fishes collected within Peru's oldest and largest petroleum concession

Diana M. Papoulias[1]*, Cristina O'Callaghan-Gordo[2,3,4,5], Pilar Lizárraga[6], Frederica Barclay[7], Tami Okamoto[8], John Astete-Cornejo[6,9]

[1] E-Tech International, Santa Fe, NM, USA
[2] Faculty of Health Sciences, Universitat Oberta de Catalunya, Barcelona, Spain
[3] Barcelona Institute for Global Health (ISGlobal), Barcelona, Spain
[4] Universitat Pompeu Fabra (UPF), Barcelona, Spain
[5] CIBER Epidemiología y Salud Pública (CIBERESP), Spain
[6] Centro Nacional de Salud Ocupacional y Protección del Ambiente para la Salud, Instituto Nacional de Salud, Peru
[7] Centro de Políticas Públicas y Derechos Humanos – Perú Equidad, Peru
[8] Department of Geography, University of Cambridge, Cambridge, UK
[9] Universidad Peruana Cayetano Heredia - Facultad de Medicina Alberto Hurtado

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Abstract

More than fifty years of poor industry practices during the exploration and exploitation of petroleum in northeastern Peru have left a legacy of contamination in the headwaters of the Amazon River. This remote region is home to several Indigenous groups who rely on the natural environment to provide them with food, fiber, fuel, and medicines. There is concern that exposure to contaminants associated with petroleum extraction may be affecting the health of these Indigenous populations. To address this concern, a landscape-level cross-sectional assessment of blood and urine concentrations of potentially toxic metals, and associated factors, in the region's residents was conducted by Peru's national health institute in 2016. The study also included evaluation of metals in fish tissues consumed by the local Indigenous inhabitants. Fish species representing six trophic guilds were collected from rivers and lakes utilized for subsistence fishing. Metals associated with produced water and oil spills (arsenic, barium, cadmium, lead, and mercury) were analyzed in viscera and carcass separately. The carcasses of the majority of the fish had concentrations of arsenic and lead at detection levels. Except for mercury and barium, all metals were higher in viscera compared with carcass. Geographic differences in fish tissue metal results were detected and, in some cases, could be associated with oil industry activity as well as previously reported results of metals in people consuming these fish. Overall, the calculated target hazard quotient for fish consumption based on arsenic and mercury concentrations was greater than 1 for adults across all river basins. Safe consumption reference limits were also exceeded for lead and cadmium for children in most of the river basins. This study has provided a unique opportunity to examine fish in the dietary exposure pathway for a human subsistence population in areas contaminated by petroleum exploitation.

Keywords: Indigenous health, fossil fuel extraction, fish contamination, human health risk assessment

*Corresponding author: dpap2@yahoo.com

INTRODUCTION

Oil extraction activities in northeastern Peru have been a continuous source of environmental contamination since 1972 when petroleum exploration began. In this remote part of Peru, where four major watersheds form the headwaters of the Amazon River, hundreds of oil wells were developed over more than 600,000 ha that comprise oil concessions known as Lots 192 (previously identified as Lot 1AB) and 8 (Figure 1). The unique and harsh conditions of the rainforest, the high water cut, and the difficulty of getting the crude oil to market have been important contributing factors to the legacy of contamination observed today.

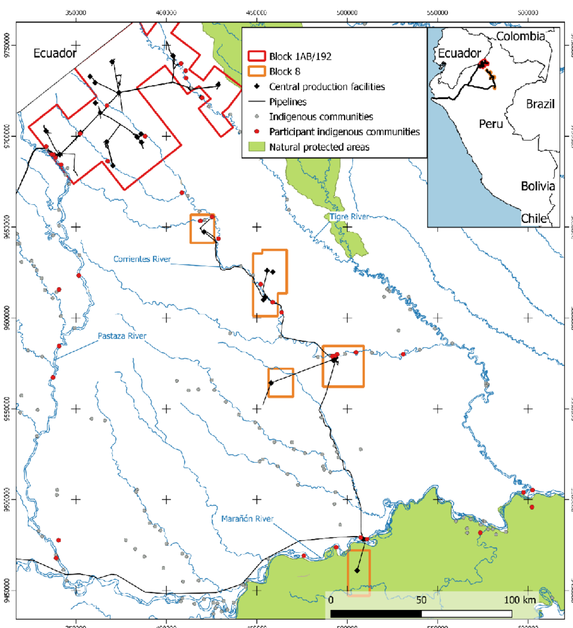

Figure 1. Map of the study area.

Environmental and social impacts, both historic and contemporary, from petroleum exploitation in lots 192 and 8 are well-documented (Fraser, 2016; PNUD, 2018; 2022). According to the data presented by E-Tech International (2025) and Leon & Zúñiga (2021) between 1997 and 2022 an estimated 669 oil spills have occurred during extraction and processing of crude or during transport via pipeline. Formation, or produced, waters have been an additional source of contaminants during oil extraction. Until 2008, when this effluent was required to be reinjected into deep wells, nearly a million barrels of highly saline produced water was released daily directly to the environment (Yusta-Garcia *et al*., 2017). Contaminants of concern for human and wildlife health related to these and other sources (e.g., drilling muds, diesel spills) predominantly include PAHs and potentially toxic metals such as arsenic (As), barium (Ba), cadmium (Cd), mercury (Hg), lead (Pb), and vanadium (V) (Johnston *et al*., 2019).

Studies in this region of Peru have reported elevated metal concentrations in water, sediments, and fish captured near the oil platforms (OEFA, n.d.; PNUD, 2018; 2022; Rosell-Melé *et al*., 2018) and in blood and urine of local residents (Anticona *et al*., 2012; O'Callaghan-Gordo *et al*., 2018; 2021; 2023). Within or near the boundaries of the two oil lots live approximately 25,000 people from five ethnic Indigenous groups. People in these Achuar, Quechua, Kichwa, Uraina, and Kukama communities largely live a subsistence lifestyle. Fish are a dietary staple and almost all parts of the fish are consumed (Rondoni, 2022; Sirén, 2011). Amazonian fishes are unique in their strong trophic connection with the terrestrial environment due to unusually high rainfall (3 m/year) and seasonal forest flooding, which may make them more likely to be exposed to contaminants associated with petroleum extraction activity.

Herein, we describe the results from contaminant tissue analysis of fish collected from communities near the oil platforms and pipelines and the relationship between fish consumption and human exposure to potentially toxic metals. This study is part of a larger cross-sectional epidemiological study that attempted to identify factors associated with indicators of residents' exposure to potentially toxic metals and hydrocarbons (MINSA, 2017).

MATERIALS AND METHODS

Description of study location

The study was conducted between July and August 2016 and led by CENSOPAS-INS, the center for occupational and environmental health of the Peruvian National Institute of Health, with the participation of external researchers and in collaboration with the Indigenous federations representing communities affected by the two oil concessions. Fish sampling took place in communities located in the Corrientes, Marañón, Pastaza, and Tigre river basins of Loreto Department, Peru. Communities from these four river basins were classified across three strata using data from OEFA-EM, the Environmental Assessment and Control Agency of the Peruvian Ministry for the Environment, to select a subset of communities representing differing levels of nominal exposure to contaminants attributed to oil-related activities.

We selected all communities from stratum 1 (communities located at < 50 km from oil extraction-related infrastructures), to ensure representation of communities potentially exposed to the highest levels of contamination, and we randomly selected 45% of communities from strata 2 and 3 (communities located between ≥ 50 - 200 km and at ≥ 200 km, respectively). Overall, 39 communities were selected: 16 from Corrientes, 8 from Marañón, 11 from Pastaza, and 4 from Tigre.

Sample collection

A total of 15 fish, 3 to 5 individuals per species, were targeted for collection from each community. Community fishers were instructed to collect fish from lotic and lentic habitats most often used for subsistence fishing and to collect species representative of a variety of trophic guilds. Fish were maintained live until processed. Viscera was separated from the fish carcass (whole body with head and gills) and separately weighed. Viscera and carcass were each wrapped in aluminum foil, labeled, placed in Ziploc© bags and kept on ice until moved to a freezer. Viscera and carcass were analyzed separately because the Indigenous peoples in this study eat the whole fish including many parts of the viscera.

Sample analysis

Samples were maintained at 4 ºC until and during transport to the laboratory for analysis at Inspectorate Services Peru, SAC, Lima, Peru, following procedures approved by CENSOPAS (2013). Fish tissues (viscera and carcass without viscera) were analyzed without pooling of samples or sub-sampling for As, Ba, Cd, Hg and Pb using ICP-MS according to protocol EPA 6020A (EPA, 2007). Sample blanks, certified reference materials (CRMs), and duplicates of the samples (10% of the load) were included with each set of fish samples for quality control purposes. Detection limit (DL), Quantification limit (QL) and percentage recovery for the measured metals are presented in Table 1.

Table 1. Detection limits (DL), quantification limits (QL), % recovery and results of duplicates used in analysis of potentially toxic metals.

Metal	DL	QL	% Recovery	Duplicates (D1/D2)
Arsenic - As	0.25	0.5	100.8	0.8
Barium - Ba	0.03	0.05	93.8	2.9
Cadmium - Cd	0.025	0.05	104.9	1.5
Mercury - Hg	0.015	0.03	97.8	1.6
Lead - Pb	0.25	0.5	106.7	0.7

Data analysis

Metals concentrations are reported as medians because the range of concentrations varied over orders of magnitude. The DL was used in all calculations of median values and statistical analyses without censoring with either the DL/2 (applicable when non-detects are fewer than 15%) because of the high number of samples reported as < DL or the Kaplan-Meier estimate of the median (useful when non-detects are between 15% and 50%) because it tended to overestimate the median when compared to using the DL directly. In tables, when more than 50% of sample values were at DL, the median is reported as < DL.

An estimate of whole fish metal concentration was derived for each fish using the following formula:

$$\frac{(MCv \cdot Wv) + (MCc \cdot Wc)}{Wt} \quad (1)$$

Where *MCv* is the metal concentration in viscera, *Wv* is the weight of viscera, *MCc* is the metal concentration in carcass without viscera, *Wc* is the weight of carcass without viscera, and *Wt* is total weight of fish. Total fish wet weight was calculated by adding viscera and carcass weights.

Statistical comparisons of differences in overall median metals concentrations between viscera and carcass and between fish captured in lentic and lotic habitats were tested using the Wilcoxon signed-rank test. The Kruskal-Wallace rank test with Dwass-Steel-Chritchlow-Fligner for pair-wise comparisons was used to test for differences in median fish metal concentrations among river basins and among trophic guilds. Collected fish species (Supplemental material 1) were classified into one of six trophic guilds according to their feeding habits in FishBase (2020) and García-Dávila *et al.* (2018): detritivore, zooplanktivore/herbivore, omnivore (detritus, no fish), omnivore (no detritus, fish), carnivore (zoobenthos and fish), or piscivore. For watershed comparisons, percentiles were also calculated based on the full dataset of tissue measurements. Fisher's exact test identified river basin differences in the proportion of fish in the top 25% of concentrations for one or more metals in either tissue. Significance level was set at alpha = 0.05 for all statistical tests. Data analysis used Excel with the Real Statistics Resource Pack software (Zaiontz, 2026) and SYSTAT v13 (SYSTAT software Inc., 2017).

Human Health Risk Assessment

Non-carcinogenic risk to adults and children of fish consumption was determined separately by estimating the Average Daily Potential Dose (ADD) for each metal and dividing this value by the reference dose (RfD µg kg^{-1} d^{-1}; As = 0.3, Ba = 200, Cd = 1.0, Hg = 0.3, Pb = 1.5; (EFSA, 2010; USEPA, 2024). The daily intake was calculated using the following equation:

$$ADD = (IR \cdot Ci) \cdot (BW) - 1 \qquad (2)$$

Where IR is the intake ratio (kg $person^{-1}day^{-1}$, wet weight), Ci is the concentration of the element in the fish tissue (µg kg^{-1}) and BW is the mean corporal weight of an adult (70 kg) or a child (18.6 kg) (USEPA, 2014). Estimates were made for each river basin region using mean whole fish concentrations (calculated from carcass and viscera; where values at DL were replaced with DL/2) following USEPA guidance (USEPA, 2026) to obtain a risk ratio or Target Hazard Quotient (THQ).

Adult IR was estimated from data collected through interviews conducted between May 24 – 31, 2019 of eight randomly selected families consisting of 53 individuals from three communities representing three of the four river basins where fish were collected (A. Alfaro, personal communication June 1, 2019). Interviews were conducted by a trained interviewer from Perú Equidad (Lima, Peru) with a local interpreter using a semi-structured questionnaire approved by community leaders. The purpose of the interviews and how the information would be used was explained to each family; all freely consented to be interviewed. Initially, the interviewer attempted to obtain the quantity of fish consumed daily by each family member. However, the cook, usually the matriarch, and the fisher, usually the patriarch, were more comfortable and confident describing weekly fish consumption and meal production for the family as a whole. Therefore, the interviewer collected information on the species of fish caught, meal portion size, and the number of meals of a given species during a week's time for the entire family. The quantity of fish eaten per family per week was estimated according to species. The whole wet weight of a fish species was estimated based on the average weight of that species captured during the present 2016 study. The number of individuals living in the home was reported however, the families noted that the number eating could vary depending on how many family members were in the home at any given time. Ages of family members were not reported. Consumption rate estimate per person in a family assumed all members were > 6 years old. Consumption ranged from 89 – 522 g $person^{-1}$ day^{-1} with average consumption as 180 g $person^{-1}$ day^{-1} ± 141 (Supplemental Material 2 Table 2.1). Portion size and meal frequency was similar across families with the exception of the family with the highest overall consumption rate (522 g $person^{-1}$ day^{-1}). It is possible that the fish collected by this family was smaller than the average size we used or that the family mistakenly reported portion size. This result was not censored because overall values for these families were within the range of fish consumption rates (66 – 550 g $person^{-1}$ day^{-1}) from a review of studies from Amazonian subsistence fishing communities (Supplemental Material Table 2.2). The data collected in those studies were obtained using a variety of methods ranging from estimates from regional fish capture data to detailed temporal dietary studies. Some studies involved hundreds of participants but one study followed one family intensely for an entire year. All studies concluded that Amazonian subsistence communities are among the highest, if not the highest, consumers of fish globally. Rondoni (2022) specifically reported on fish consumption in Indigenous communities along the Marañón River in Loreto and noted that 72% of interviewees eat fish every day with many eating it more than once a day, suggesting we may be slightly under estimating consumption. Many studies reviewed pointed out that fish consumption in riverine Amazonian communities is variable throughout the year depending on whether water levels are high (fish dispersed and difficult to catch) or low and that species composition will also be variable. Notably, during May the river levels in the region of our study are high suggesting that the reported weekly fish capture for the families we interviewed may be on the low end of the yearly catch distribution. Generally, USEPA guidance cites an average of 142 g $person^{-1}$ day^{-1} for subsistence fisher populations but notes that Native American tribal members living in riverine communities may eat up to 540 g d^{-1} (USEPA, 2000).

None of the Amazonian studies reviewed reported consumption by age class of family members. Therefore, we derived consumption for 3 to 6 year-old children using data in a report for a North American Native American Columbia River fishing community where consumption was reported separately for adults and children < 5 years old as 59 g d^{-1} and 11 g d^{-1} on average, respectively (USEPA, 2011). These average rates are low compared to the Amazonian communities. However, the rate for the 95th percentile of this population was 170 g person^{-1} day^{-1} and 98 g person^{-1} day^{-1} for adults and children, respectively. The adult rate for this subset of the Columbia River population is comparable to our data and therefore we chose to use this relationship (98 g:170 g; 58%) to estimate the daily consumption rate of children (3 to 6 years old) in our study: 58% of 180 g adult^{-1} day^{-1} = 104 g child^{-1} day^{-1}. We also note that the USEPA default meal size for children used in calculations of fish consumption-related risk assessments is 85 g, comparable to our derived value of 104 g person^{-1} day^{-1} (USEPA, 2000).

RESULTS

A total of 228 fish representing 28 species were collected from 29 lotic and lentic habitats from the four watersheds (Table 2). Individual fish wet weights ranged from 20 g to 1040 g with a median weight of 130 g.

Approximately, 90% of eviscerated carcass sample concentrations were at or below the DL for As and Pb from all four watersheds (Table 3). Barium concentrations were above DL for all samples and most samples analyzed for Hg. The percentage of samples at or below DL was variable across watersheds for Cd relative to the other metals analyzed.

There were no significant differences in median concentrations of metals between fish collected in lotic and lentic habitats; the percentage of fish at or below DL from each habitat was the same (Table 4). Median concentrations of only Ba and Hg varied according to fish trophic guild. Barium was highest in omnivores and lowest in carnivores and zooplanktivore/herbivores. Mercury was lowest in the zooplanktivore/herbivores and highest in carnivores but this group was not statistically different from bottom-feeding omnivores and detritivores. Similarly, median Hg concentration was elevated in piscivores and this group was statistically similar to fish-eating omnivores (Table 4).

Table 2. Description of fish collected from four river basins near oil extraction activity.

Watershed	Total number of fish	Number fish in a trophic guild						Number species	Number Habitats	
		1	2	3	4	5	6		Lentic	Lotic
Corrientes	64	18	10	17	3	13	3	14	10	3
Marañón	66	28	12	6	4	14	2	14	2	3
Pastaza	56	13	8	19	0	15	1	20	4	3
Tigre	42	9	0	10	5	17	1	11	4	0

Note: Trophic guilds: 1 = detritivore, 2 = zooplanktivore/herbivore, 3 = omnivore (no fish), 4 = omnivore (no detritus), 5 = carnivore (zoobenthos and fish), 6 = (piscivore).

Table 3. Percent (%) of samples at or below the detection limit (mg kg^{-1}; in parenthesis).

	As (0.25)		Ba (0.03)		Cd (0.025)		Hg (0.015)		Pb (0.25)	
Watershed	C	V	C	V	C	V	C	V	C	V
Corrientes	89 %	48 %	0 %	0 %	69 %	16 %	2 %	11 %	92 %	50 %
Marañón	95 %	74 %	0 %	0 %	88 %	24 %	2 %	6 %	95 %	70 %
Pastaza	91 %	66 %	0 %	0 %	56 %	21 %	2 %	7 %	88 %	62 %
Tigre	98 %	50 %	0 %	0 %	33 %	5 %	0 %	7 %	95 %	55 %

Note: C = carcass. V = viscera.

Table 4. Median concentrations (mg kg^{-1} wet weight) of metals in whole fish.

	N	As	Ba	Cd	Hg	Pb
Habitat						
Lentic	146	0.25	3.63	0.03	0.26	< DL
Lotic	78	< DL	1.93	0.03	0.36	< DL
Trophic guild						
Detritivore	70	0.29 (0.13)	5.11 A (11.09)	0.06 (0.15)	0.23 A (0.20)	0.26 (0.15)
Zooplanktivore/herbivore	30	< DL	3.32 B (5.23)	0.12 (0.23)	0.10 B (0.30)	< DL
Omnivore (no fish)	62	< DL	16.47A (37.43)	0.09 (0.15)	0.24 A (0.31)	0.25 (0.09)
Omnivore (no detritus)	12	<DL	10.82 C (26.00)	0.21 (0.25)	0.27 C (0.33)	0.26 (0.05)
Carnivore (zoobenthos and fish)	47	< DL	2.01 D (5.46)	0.06 (0.11)	0.70 A (0.61)	< DL
Piscivore	7	< DL	9.30 E (44.48)	0.04 (0.26)	0.46 C (0.20)	0.25 (0.36)

Note: Interquartile range (IQR) in parenthesis. Trophic guilds with the same letter are not significantly different (p-values > adjusted alpha 0.003). When more than 50% of samples are at detection limit (DL), the median is reported as < DL.

More than fifty percent of the carcass and viscera samples for As and Pb were below the detection limit nevertheless, viscera concentrations were greater than carcass for the subset of fish with concentrations above DL in either matrix for As (n = 98; medianViscera = 1.03 mg kg^{-1}, medianCarcass = 0.25 mg kg^{-1}; $p < 0.0001$) and Pb (n = 94, medianViscera = 1.29 mg kg^{-1}, medianCarcass = 0.25 mg kg^{-1}; $p < 0.0001$). Similarly, viscera Cd was greater than the concentration in carcass samples (n = 196, medianViscera = 0.55 mg kg^{-1}, medianCarcass = 0.025 mg kg^{-1}, $p < 0.0001$). Conversely, median Hg concentration was greater in carcass than viscera ($p < 0.0001$). Median Ba concentrations did not differ between carcass and viscera (p = 0.203).

Watershed comparisons

Watersheds differed in carcass metal concentrations only for Ba and Cd. Median Ba concentration was greatest in carcass tissues from the Tigre basin followed by the Corrientes; however, Ba concentrations were statistically similar for fish from the Pastaza and Tigre. Median Cd concentration was greatest for Tigre fish with clear statistical differences only between fish sampled from the Corrientes and Tigre basins (Table 5). Viscera concentrations of As, Ba, Cd, and Pb were statistically greater in Corrientes basin fish than those from the Pastaza. Viscera As, Ba, and Pb were also significantly greater in Corrientes fish compared to fish from the Tigre basin. The concentrations of As and Ba in Tigre basin fish viscera were greater than for fish from the Marañón and Pastaza. Cadmium viscera was also greater in Tigre fish than Corrientes and Marañón fish. Viscera Cd was greater in Pastaza basin fish than those from the Marañón but fish from these basins had similar viscera concentrations of Ba. Although Pastaza and Marañón median As and Pb viscera concentrations were the same (at DL), statistically they differed. The same was true for viscera Pb among fish collected from the Tigre, Pastaza and Marañón watersheds. Mercury viscera concentrations were similar among the watersheds (Table 5).

Table 5. Median concentration (mg kg^{-1}), range (in parenthesis) of metals in carcass and viscera for the entire study and by watershed.

River Basin Tissue	N	As [0.1 - 0.2]	Ba	Cd [0.05 – 0.25]	Hg [0.5]	Pb [0.3]
All basins	228					
Carcass		< DL	2.99	< DL	0.3	< DL
Viscera		< DL*	4.4	0.42 *	0.16 *	< DL*
Corrientes	64					
Carcass		< DL A (0.25 - 2.2)	3.98 A (0.53 -167.06)	< DL A (0.03 - 3.82)	0.27 A (0.02 - 1.82)	< DL A (0.25 - 1.93)
Viscera		0.54 a (0.25 - 4.36)	6.53 a (0.36 - 713.51)	0.55 a (0.03 - 10.34)	0.14 a (0.02 - 1.76)	0.38 a (0.25 - 11.64)
Marañón	66					
Carcass		< DL A (0.25 - 4.16)	1.65 B (0.2 - 97.25)	< DL AB (0.03 - 2.61)	0.37 A (0.02 - 2.44)	< DL A (0.25 - 7.4)
Viscera		< DL a (0.25 - 5.79)	1.2 b (0.09 - 174.31)	0.27 a (0.03 - 9.77)	0.25 a (0.02 - 2.77)	< DL a (0.25 - 10.84)
Pastaza	56					
Carcass		< DL A (0.25 - 5.11)	1.79 C (0.09 - 2850.08)	< DL BC (0.03 - 33.25)	0.34 A (0.02 - 9.93)	< DL A (0.25 - 2.98)
Viscera		< DL b (0.25 - 13.55)	3.485 b (0.14 - 280.69)	0.29 b (0.03 - 7.79)	0.15 a (0.02 - 5.02)	< DL b (0.25 - 4.86)
Tigre	42					
Carcass		< DL A (0.25 - 0.52)	16.82 C (0.29 - 435.96)	0.07 C (0.03 - 0.22)	0.24 A (0.04 - 2.95)	< DL A (0.25 - 2.41)
Viscera		0.38 c (0.25 - 4.6)	9.14 c (0.08 - 577.92)	1.53 b (0.03 - 15.18)	0.16 a (0.02 - 1.36)	< DL c (0.25 - 6.31)

Note: Significant difference indicated by an asterisk. Within a metal and tissue, no significant differences across river basin is indicated by the same superscript letter ($p < 0.05$). When greater than 50% of samples are at detection limit (DL), the median is reported as < DL. The maximum allowable concentration following EU standards for fish is in [brackets] (EUR-Lex, 2023).

The 75th percentile concentration for each metal was calculated for the full set of concentrations measured in both tissues combined from fish collected from the four watersheds (Supplemental material 3). Ninety (90) percent of the fish collected overall in this study exceeded the 75th percentile concentration either for the carcass or the viscera for one or more metals. River basin differences are more clearly seen when looking at the proportion of fish with tissue metals concentrations in the top 25% of the ranges of concentrations measured (Figure 2); all tissue concentrations in this group exceeded EU maximum limits.

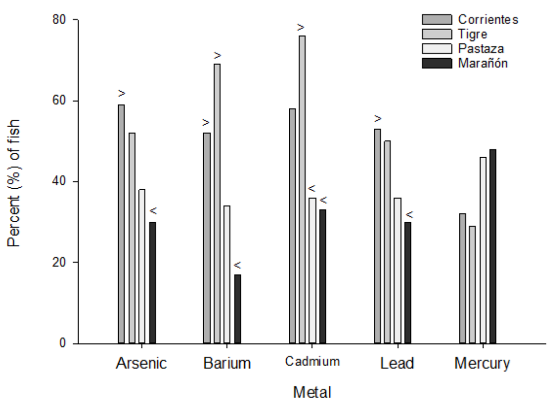

Figure 2. Proportion of fish by river basin with concentrations of metals in either viscera or carcass above the 75th percentile (As: > 0.50 mg kg^{-1},Ba: > 18.19 mg kg^{-1}, Cd: > 0.46 mg kg^{-1}, Pb: > 0.5 mg kg^{-1} and Hg: > 0.49 mg kg^{-1}) of the range of concentrations measured. Bars with > or < indicate significant differences in proportions at alpha = 0.05.

The proportion of fish exceeding the 75th percentile concentration was higher in the Corrientes and Tigre River basins compared to the Marañón and Pastaza basins for As, Ba, Cd, and Pb. Relative to the other river basins, a greater proportion of fish from the Marañón and Pastaza had high concentrations of mercury.

The risk evaluation is based on the metal concentration in the whole fish, and not viscera or muscle separately, to reflect the pattern of consumption per person over time. Arsenic and Hg exceeded the USEPA safe consumption reference limits (RfD) in fish tissues under both concentration scenarios evaluated and for adults and children (Table 6). Cadmium for adults in the Pastaza river basin also exceeded RfD. (Table 6). Additionally, concentrations of Pb and/or Cd are at levels of concern (THQ > 1) for children in all river basins except for Cd in the Marañón and Pb in the Corrientes river basins.

DISCUSSION

Analysis of potentially toxic metals in fish tissues from a large sampling in four Peruvian watersheds where oil exploitation has occurred since the early 1970s indicates concentrations of concern in some species and in some watersheds for populations dependent on subsistence fishing.

Table 6. Non-carcinogenic risk calculation for metals exposure from fish consumption by adults and children living near oil fields in Loreto, Peru.

Metal	RfD (µg kg^{-1})	Corrientes Avg. daily dose (µg kg^{-1})	Corrientes THQ	Tigre Avg. daily dose (µg kg^{-1})	Tigre THQ	Pastaza Avg. daily dose (µg kg^{-1})	Pastaza THQ	Marañón Avg. daily dose (µg kg^{-1})	Marañón THQ
Adults									
As	0.30	0.64	**2.14**	0.46	**1.52**	1.16	**3.86**	0.57	**1.89**
Hg	0.30	0.98	**3.26**	1.00	**3.34**	1.72	**5.74**	1.21	**4.03**
Pb	1.50	0.67	0.46	0.69	0.46	0.80	0.53	0.75	0.50
Cd	1.0	0.54	0.54	0.59	0.59	1.70	**1.70**	0.31	0.31
Ba	200	52.69	0.26	86.01	0.43	42.25	0.21	16.02	0.08
Children 3 to 6 years old									
As	0.30	1.40	**4.68**	1.01	**3.37**	2.53	**8.42**	1.23	**4.12**
Hg	0.30	2.13	**7.11**	2.19	**7.30**	3.76	**12.54**	2.64	**8.79**
Pb	1.50	1.46	0.97	1.52	**1.01**	1.74	**1.16**	1.63	**1.09**
Cd	1.0	1.18	**1.18**	1.29	**1.29**	3.70	**3.70**	0.67	0.67
Ba	200	115.01	0.58	187.86	0.94	92.22	0.46	34.97	0.17

Note: Calculation is based on the whole fish mean metal concentration (0.22 mg As kg^{-1}, 0.45 mg Ba kg^{-1}, 0.12 mg Cd kg^{-1}, 0.18 mg Hg kg^{-1}, and 0.25 mg Pb kg^{-1}). ADD is average daily potential dose, THQ is targeted hazard quotient. THQ > 1 are of concern.

Differences in median fish tissue concentrations of As, Ba, Cd, and Pb, but not Hg, varied slightly among the four river basins. Fishes collected from the Marañón and Pastaza river basins had lower concentrations overall of these four metals. Metals enrichment of sediments from varying land use practices or hydrogeographic differences among the habitats where these fish were collected may explain the river basin differences however, site specific environmental data are not available (Echevarría *et al.*, 2024). Although we did not detect significant differences in metals concentrations between fish collected in lentic and lotic waters, fishers in the Pastaza and Marañón basins utilized both habitats equally in contrast to fishers in the Corrientes and Tigre basins that fished mainly in lentic waters. Moreover, Pastaza and Marañón fishers utilized the mainstem rivers as or more frequently than smaller tributaries. Fishes in the large mainstem rivers are less likely to be exposed to oil-related contaminants because the extractive activities largely occur in the upper parts of the watersheds along smaller tributaries. Watershed differences are not easily explained.

Fish tissue metals data are scarce for the river basins we studied. Brousett-Minaya *et al.* (2024) analyzed metals in fish tissues from the Corrientes, Pastaza and Tigre rivers as part of a risk assessment. Arsenic, Cd, and Pb concentrations in fish muscle tissues were lower than those in our study but Hg concentrations were similar. Whereas Brousett-Minaya *et al*. (2024) only analyzed fish from the mainstem rivers, the majority of fish in our study were from smaller water bodies where fishers most often fish and which may have been more impacted by oil activities. Webb *et al.* (2015) measured Hg in *Hoplias malabaricus*, a piscivorous fish, from the Pastaza (0.17 ± 0.02 mg kg^{-1}) and Corrientes (0.15 ± 0.03 mg kg^{-1}) rivers and suggested petroleum-contaminated sediments could be a source. Although median Hg concentrations generally for the carnivorous and piscivorous species in the present study were greater than for *H. malabaricus* reported by Webb *et al*. (2015), average Hg concentration for comparable size *H. malabaricus* (mean 0.68 ± 0.60 mg kg^{-1}, range 0.17 ± 2.86 mg kg^{-1}, n = 20) was four times that of Webb *et al.* (2015). The OEFA (2016) collected a limited number of fish for metals analysis during identification of contaminated sites in the Corrientes, Pastaza, and Tigre basins. Mercury concentrations in fish muscle tissue from the Pastaza were lower (0.07 – 0.18 mg kg^{-1}, n = 4) whereas those of fish from the Corrientes (0.28 – 0.78 mg kg^{-1}, n = 2) and Tigre (0.28 – 1.26 mg kg^{-1}, n = 4) basins were greater than the median concentrations measured in this study in fish carcasses from these same basins. Arsenic, Cd, and Pb for these same OEFA (2016) samples were at or below DL comparable to the median values in the present study excepting Cd in Tigre basin fish (median 0.07 mg kg^{-1}). In another study, fishes collected from the Corrientes River near oil platforms, storage tanks, and ducts had similar concentrations of Cd (mean 0.12 mg kg^{-1}, range 0.07 – 0.19) as fishes studied here whereas, Hg and Pb were relatively lower (SANIPES, 2019). Size of fish, the species collected, specific location as well as analytical procedures could account for the differences among these studies.

The distribution and bioaccumulation of metals among fish tissues can vary depending on a metal's specific chemical properties as well as biotic and abiotic factors. In the present study, median metals concentrations were generally higher in the viscera than the carcass, excepting Hg and barium. Arsenic, Cd, and Pb tend to accumulate in liver and kidney whereas, Hg accumulates in muscle (Jamil *et al.*, 2023; Kumar & Singh, 2010). Although Ba concentrations tend to be greater in fish liver than muscle, there may be species differences (Fletcher *et al*., 2014).

Trophic guild feeding behavior can affect the likelihood of a fish's exposure to metals. Across trophic guilds, only Ba, and Hg tissue concentrations significantly differed. Barium and arsenic accumulate in sediments exposing benthic organisms consumed by detritivores (Sharma *et al*., 2025; Wang *et al*., 2023). Barium, Cd, and Pb can also exist as dissolved ions that can directly contaminate a fish during respiration.

There is evidence that uptake of divalent metal cations such as Ba and Cd is greater in freshwaters with low hardness and low pH (Perera *et al.*, 2015), a characteristic of most aquatic habitats in these Amazonian watersheds. In the present study, Ba was highest in bottom-feeding omnivores and statistically similar to detritivores and As was < DL in more than 50% of fishes from all trophic groups except detritivores. Mercury concentrations tend to be greatest in fish at the top of the food chain because Hg accumulates in prey tissues and biomagnifies in predators (Kidd *et al.*, 2011). Vega *et al.* (2024) reported concentrations of Hg by fish trophic guild in the Peruvian Amazon of Loreto, outside of the influence of oil exploitation, to provide baseline information before river dredge mining in the region becomes more prevalent. Concentrations were generally similar to those reported here with carnivorous species having the highest concentrations.

Harmful levels of metals in foods are typically determined by regulatory agencies after considering the metal's toxicity and dietary exposure. In addition, the vulnerability of the potentially exposed population may also be considered as well as the nutritional importance of the food item in the diet of the population. Fish are a key staple in the subsistence diets of the people living in these four river basins and therefore exposure to heavy metals may be greater for these Indigenous peoples. These groups commonly consume nearly all the parts of a fish and the practice of consuming "ishpa", or fish intestines, is prevalent among many of the communities in this study.

Overall, ninety percent of fishes exceeded EU limits for one or more metals in either viscera or carcass tissue. Across watersheds, median carcass metal concentrations were within EU allowable limits as a result of the high number of samples measuring at the DL, whereas median viscera metals concentrations tended to exceed EU limits. The DL for As was slightly above the EU limit and could not be fully evaluated. Barium is rarely found in high concentrations in foods and therefore countries have not established guidance levels. Median Ba concentrations in fish from the present study were up to 100 times greater than the concentration in fresh fish from a Canadian diet study (median 0.02 mg kg^{-1} ww range 0.002 – 0.111; Health Canada, 2005).

Risk characterization indicated that safe reference levels based on consumption of whole fish were exceeded for some metals. Arsenic and Hg were the metals of concern in adult diets for all four river basins and additionally Cd for those living in the Pastaza river basin. The risk to children includes Pb and Cd, the exception being Cd for children in the Marañón river basin. Brousett-Minaya *et al.* (2024) measured As, Cd, Hg and Pb in fish muscle collected directly from Corrientes, Tigre and Pastaza rivers and calculated non- carcinogenic risk for consumption by adults. In their study, risk was indicated only for mercury. Average concentrations of As, Cd, and Pb in Brousett-Minaya *et al.* (2024) tended to be lower than we report with the exception of similar results for mercury. Sampling location (large rivers vs. smaller surface waters), proximity to oil infrastructure and our inclusion of viscera in the analysis could explain some of the differences in the results between our studies.

Petroleum industry-related environmental contaminants, particularly metals, have long been postulated as a toxic threat to the Indigenous people living in and near oil concessions 192 and 8 in northeastern Loreto (Anticona *et al.*, 2011). Lead and mercury have been the metals most carefully evaluated for an association between environmental exposure and toxic levels in these inhabitants but results have been inconclusive. O'Callaghan *et al*. (2021) reported river basin differences in blood lead levels (BLL) in people from the same communities where fish in the present study were collected. Highest BLLs were in the Corrientes inhabitants and lowest in the Marañón. Consumption of ishpa was identified as one of the risk factors for the higher blood lead levels. Although Anticona *et al.* (2013) also reported high BLLs associated with fishing activity, muscle tissue levels of analyzed fish were low. These results are consistent with those of the present study in that the highest median concentrations of Pb were in viscera of fish from the Corrientes river basin, whereas all basins had median concentrations of Pb in muscle at the level of detection. In contrast to Pb, urine Hg levels were highest in inhabitants of the Marañón river basin and also associated with self-reported fish consumption (O'Callaghan *et al.*, 2023). Webb *et al.* (2016) found elevated Hg levels in urine in people from the Corrientes and Pastaza riverine communities (Pastaza > Corrientes) but this was not associated with the number of fish meals. Median Hg concentrations in fish muscle in our study were also highest in those captured in the Marañón and Pastaza river basins however statistically there were no concentration differences among the river basins. Urine Cd levels were highest in peoples living in the Corrientes and Tigre basins, considered the most polluted of the four river basins (O'Callaghan *et al*., 2023). Similarly, fish viscera from the Corrientes and Tigre were higher in Cd than the other two river basins.

Fishes in the four river basins may be exposed to heavy metals accumulated in lotic or lentic sediments coincident with decades of oil extraction activity as has been found in oil producing regions of Nigeria (Ninibarini & Bernard, 2015). Metals concentrations in crude oils are generally low relative to soils (Magaw *et al*., 1999) but the associated highly saline produced water can have greater concentrations (Neff *et al.*, 2011) such as is found in the watersheds in the present study (Yusta-García *et al*., 2017). Although this study was not designed to determine sources of metals in fish, evidence exists, from other regions of intense oil exploitation, of associations between metals-contaminated sediments and metals accumulation in aquatic biota (Abarshi *et al.*, 2017). The practice in these Peruvian oil fields for a decade was to dispose of millions of liters of highly saline produced water into or near surface waters. Metals from this waste, drilling muds, and crude oil spills potentially contaminate sediments affecting fish in these basins; however, establishing a definitive causal link requires targeted studies at the appropriate spatial scales.

Fish tissues collected near two oil leases, with a documented history of extensive environmental contamination, had elevated concentrations of some metals. Indigenous communities in this area depend on fish as an important source of protein. Metals exposure from fish are at levels of concern and may be associated with earlier reports of these metals in blood and urine of the inhabitants. The health risks from subsistence consumption of these fish may be reduced by avoiding consumption of the viscera and choosing lower trophic guild species.

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AUTHOR CONTRIBUTIONS

DP: Conceptualization, Methodology, Formal analysis, Visualization, Writing – original draft preparation, Writing – review & editing. **CO**: Conceptualization, Methodology, Supervision, Project administration. **PL**: Data curation, Investigation. **FB**: Conceptualization, Funding acquisition, Project administration, Supervision, Writing – original draft. **TO**: Conceptualization, Investigation, Supervision, Project Administration, Funding acquisition. **JA**: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision.

REFERENCES

Abarshi, M. M., Dantala, E. O., & Mada, S. B. (2017). Bioaccumulation of heavy metals in some tissues of croaker fish from oil spilled rivers of Niger Delta region, Nigeria. Asian Pacific Journal of Tropical Biomedicine, 7(6), 563–568. https://doi.org/10.1016/j.apjtb.2017.05.008

Anticona, C., Bergdahl, I. A., Lundh, T., Alegre, Y., & Sebastian, M. S. (2011). Lead exposure in Indigenous communities of the Amazon basin, Peru. International Journal of Hygiene and Environmental Health, 215(1), 59–63. https://doi.org/10.1016/j.ijheh.2011.07.003

Anticona, C., Bergdahl, I. A., & Sebastian, M. S. (2012). Lead exposure among children from native communities of the Peruvian Amazon basin. Revista Panamericana de Salud Pública, 31(4), 296–302.

Anticona, C., Coe, A.-B., Bergdahl, I. A., & San Sebastian, M. (2013). Easier said than done: Challenges of applying the Ecohealth approach to the study on heavy metals exposure among Indigenous communities of the Peruvian Amazon. BMC Public Health, 13(1), 437. https://doi.org/10.1186/1471-2458-13-437

Brousett-Minaya, M. A., Chu-Koo, F. W., Napuchi-Linares, J., Zambrano Panduro, C. E., Reyes-Larico, J. A., Larrea-Valdivia, A. E., & Biamont-Rojas, I. E. (2024). Consumption of native fish associated with a potential carcinogenic risk for Indigenous communities in the Peruvian Amazon. Toxics, 12(8), 552. https://doi.org/10.3390/toxics12080552

Centro Nacional de Salud Ocupacional y Protección del Ambiente para la Salud - CENSOPAS. (2013). Efectos de la exposición crónica a metales pesados y su manejo clínico: Revisión Rápida. https://cdn.www.gob.pe/uploads/document/file/4120479/06_SERIE_NOTA_TECNICA_N_06-2013_Efectos_de_la_exposicion_cronica_a_metales_pesados_y_su_manejo_clinico.pdf

Echevarría, G., Lujan, N.K., Montoya, J., Granda-Albuja, M.G., Vladiviezo-Rivera, J., Sánchez, F., Cuesta, F., & Ríos-Touma, B. (2024). Abiotic and biotic factors influencing heavy metals pollution in fisheries of the Western Amazon. Science of the Total Environment, 908, 168506. https://doi.org/10.1016/j.scitotenv.2023.168506

European Food Safety Authority - EFSA. (2010). Scientific opinion on lead in food. EFSA Journal, 8,1570.

E-Tech International. (2025, November 25). The history and geography of oil spills in the Peruvian Amazon. E-Tech International (Accessed 25 April 2025).

https://etechinternational.org/the-history-and-geography-of-oil-spills-in-the-peruvian-amazon/

EUR-Lex. (2023). EUR-lex - 02006R1881-20230326. Available at: https://eur-lex.europa.eu/eli/reg/2006/1881/2023-03-

26/eng (Accessed: 23 April 2026).

FishBase. (2020). From https://www.fishbase.se/ (Accessed 22 March 2025)

Fletcher, D.E., Lindell, A.H., Stillings, G.K., Mills, G.L., Blas, S.A., & McArthur, J.V. (2014). Variation in trace-element accumulation in predatory fishes from a stream contaminated by coal combustion waste. Archives of Environmental Contamination and Toxicology, 66, 341-360. https://doi.org/10.1007/s00244-013-9984-3.

Fraser, B. (2016). A rash of spills in the Amazon has scientists and villagers scrambling to understand oil's effects on the ecosystem. Science, 353(6300), 641-643.

Garcia, R., (1995). Contaminación ambiental en la Amazonía Peruana. Instituto de Investigaciones de la Amazonía Peruana. Dirección General de Conservación de Medio Ambiente. https://repositorio.iiap.gob.pe/items/7cb8bcf2-5fa3-40d5-8bf5-9f2c6ac424d5

García-Dávila, C., Sánchez, H., Flores, M., Mejia, J., Angulo, C., Castro-Ruiz, D., Estivals, G., García, A., Vargas, G., Nolorbe, C., Núñez, J., Mariac, C., Duponchelle, & F., Renno, J.-F. (2018). Peces de consumo de la Amazonía Peruana. Instituto de Investigaciones de la Amazonía Peruana (IIAP). https://sinia.minam.gob.pe/documentos/peces-consumo-amazonia-peruana

Health Canada. (2005). Canadian Total Diet Study - Trace Elements 1993-2018 - Open Government Portal. (n.d.). https://open.canada.ca/data/en/dataset/83934503-cfae-4773-b258-e336896c2c53

Jamil Emon, F., Rohani, M. F., Sumaiya, N., Tuj Jannat, M. F., Akter, Y., Shahjahan, M., Abdul Kari, Z., Tahiluddin, A. B., & Goh, K. W. (2023). Bioaccumulation and bioremediation of heavy metals in fishes—A review. Toxics, 11(6), 510. https://doi.org/10.3390/toxics11060510

Johnston, J.E., Lim, E., & Roh, H., (2019). Impact of upstream oil extraction and environmental public health: A review of the evidence. Science of the Total Environment, 657, 187-199. https://doi.org/10.1016/j.scitotenv.2018.11.483

Kidd, K., Clayden, M. & Jardine, T. (2011). Bioaccumulation and biomagnification of mercury through food webs. In G. Liu, Y. Cai & N. O'Driscoll (Eds.), Environmental chemistry and toxicology of mercury. https://doi.org/10.1002/9781118146644.ch14

Kumar, P., & Singh, A. (2010). Cadmium toxicity in fish: An overview. GERF Bulletin of Biosciences 1(10), 41-47.

Leon, A., & Zúñiga, M. (2021). The shadow of oil: A report on oil spills in the Peruvian Amazon from 2000 to 2019. Oxfam. https://oi-files-cng-v2-prod.s3.eu-west-2.amazonaws.com/peru.oxfam.org/s3fs-public/file_attachments/The%20shadow%20of%20Oil.pdf

Ministerio de Salud; Instituto Nacional de Salud - MINSA. (2017). Niveles y Factores de Riesgo de Exposición a Metales Pesados e Hidrocarburos En Los Habitantes de Las Comunidades de Las Cuencas de Los Ríos Pastaza, Tigre, Corrientes y Marañón Del Departamento de Loreto; Ministerio de Salud: Lima, Peru.

Magaw, R. I., McMillen, S. J., Gala, W. R., Trefry, J. H., & Trocine, R. P. (1999). A risk evaluation of metals in crude oils. SPE/EPA Exploration and Production Environmental Conference. https://doi.org/10.2118/52725-ms

Neff, J., Lee, K., & DeBlois, E. M. (2011). Produced water: Overview of composition, fates, and effects. In K. Lee & J. Neff (Eds.), Produced water (pp. 3–54). New York: Springer. https://doi.org/10.1007/978-1-4614-0046-2_1

Ninibarini, Z. & Benard, B.B. (2015). Trace metals in intertidal sediment of mangrove-sheltered creeks in Niger Delta, Nigeria: Variability before and after crude oil spillage. African Journal of Environmental Science and Technology, 9(4), 371-378. https://doi.org/10.5897/AJEST2015.1875

O'Callaghan-Gordo, C., Flores, J. A., Lizárraga, P., Okamoto, T., Papoulias, D. M., Barclay, F., Orta-Martínez, M., Kogevinas, M., & Astete, J. (2018). Oil extraction in the Amazon basin and exposure to metals in Indigenous populations. Environmental Research, 162, 226–230. https://doi.org/10.1016/j.envres.2018.01.013.

O'Callaghan-Gordo, C., Rosales, J., Lizárraga, P., Barclay, F., Okamoto, T., Papoulias, D. M., Espinosa, A., Orta-Martinez, M., Kogevinas, M., & Astete, J. (2021). Blood lead levels in Indigenous peoples living close to oil extraction areas in the Peruvian Amazon. Environment International, 154, 106639.https://doi.org/10.1016/j.envint.2021.106639

O'Callaghan-Gordo, C., Rosales, J., Lizárraga, P.,Barclay, F., Okamoto, T., Papoulias, D. M., Espinosa, A., Orta-Martinez, M., Kogevinas, M., & Astete, J. (2023). Levels of arsenic, cadmium, and mercury in urine of Indigenous people living close to oil extraction areas in the Peruvian Amazon. Environmental Health Perspectives, 131(5), 057701.

https://doi.org/10.1289/EHP11932

Organismo de Evaluación y Fiscalización Ambiental - OEFA. (n.d.). Sitios impactados por actividad de hidrocarburos – Sitio Ley 30321. Reporte de sitios impactados. Ministerio del Ambiente. Retrieved January 1, 2026, from https://oefa.maps.arcgis.com/apps/dashboards/f3a2b5d1744f4bd6be0f1ac12f51456a

OEFA. (2016). Evaluación del Lote 192 (antes Lote 1-AB) durante el año 2016. Informe No.118-2016-OEFA/DE-SDLB-CEAI. Ministerio del Ambiente, Lima, Perú. pp 2067.

Perera, P.A.C,T., Kodithuwakku, S.P., Sundarabarathy, T.V., & Edirisinghe, U. (2015). Bioaccumulation of cadmium in freshwater fish: An environmental perspective. Insight Ecology, 4(1), 1–12. https://doi.org/10.5567/ECOLOGY-IK.2015.1.12

Programa de Las Naciones Unidas para el Desarrollo - PNUD. (2018). Estudio Técnico independiente del ex lote 1AB. Lineamientos estratégicos para la remediación de los impactos de las operaciones petroleras en el ex lote 1AB en Loreto, Perú. https://www.undp.org/es/peru/publicaciones/eti-del-ex-lote-1ab

Programa de Las Naciones Unidas para el Desarrollo [PNUD]. (2022). Estudio técnico socioambiental y lineamientos estratégicos para la remediación de los impactos independiente del lote 8. Diagnóstico de las operaciones petroleras en el lote 8 en Loreto, Perú. https://www.undp.org/es/peru/publicaciones/estudio-tecnico-independiente-del-lote-8

Yusta-García, R., Orta-Martínez, M., Mayor, P., González-Crespo, C., & Rosell-Melé, A. (2017). Water contamination from oil extraction activities in Northern Peruvian Amazonian rivers. Environmental Pollution, 225, 370–380. https://doi.org/10.1016/j.envpol.2017.02.063

Rondoni, C. (2022). Extractivism and unjust food insecurity for Peru's Loreto Indigenous communities. Sustainability, 14(12), 6954. https://doi.org/10.3390/su14126954

Rosell-Melé, A., Moraleda-Cibrián, N., Cartró-Sabaté, M., Colomer-Ventura, F., Mayor, P., & Orta-Martínez, M. (2018). Oil pollution in soils and sediments from the Northern Peruvian Amazon. Science of the Total Environment, 610-611, 1010-1019.

Organismo Nacional de Sanidad Pesquera - SANIPES. (2019). Declaratoria de emergencia ambiental a la localidad de Villa Trompeteros – Nueva Libertad, Loreto. Informe N° 049-2019-SANIPES-DSNPA-SDIP. Ministerio de la Producción.

Sirén, A. (2011). El Consumo De Pescado y Fauna Acuática Silvestre en la Amazonía Ecuatoriana. COPESCAL. Documento Ocasional No 12. Roma, FAO, 2011, 37 pp.

Sharma, S., Bolan, S., Mukherjee, S., Guilherme, L. R. G., Viana, D. G., Ferreira, A. D., Myrvang, M. B., Almås, Å. R., Gjengedal, E. L. F., Cappuyns, V., Guerra, M. B. B., De Oliveira, C., Lamb, D., Siddique, K. H., & Bolan, N. (2025). Barium distribution, dynamics and fate in terrestrial and aquatic environments. Environmental Research, 287, 123059. https://doi.org/10.1016/j.envres.2025.123059

United States Environmental Protection Agency - USEPA. (2000). Guidance for Assessing Chemical Contaminant Data for use in Fish Advisories. Volume II, Risk Assessment and Fish Consumption Limits, third edition. U.S. EPA Office of Water, Office of Science and Technology.

USEPA. (2007). Method 6020A: Inductively coupled plasma-mass spectrometry, Revision 1. February 2007. https://archive.epa.gov/epawaste/hazard/testmethods/web/pdf/method%206020a%2C%20revision%201%20-%202007.pdf

USEPA. (2011). Exposure Factors Handbook: 2011 edition. Chapter 10 Intake of fish and shellfish. National Center for Environmental Assessment, Washington, DC; EPA/600/R-09/052F. http://www.epa.gov/ncea/efh

USEPA. (2014). Child-Specific Exposure Scenarios Examples (Final Report). (2017, March 20). USEPA. https://assessments.epa.gov/risk/document/&deid=262211

USEPA. (2024). Regional Screening Level (RSL)-Generic Tables; U.S. EPA: Washington, DC, USA.

USEPA. (2026, March 24). Exposure assessment tools by routes – ingestion. EPA. https://www.epa.gov/expobox/exposure-assessment-tools-routes-ingestion

Vega, C. M., Pisconte, J. N., Torres, M., Garcia, C.M., Salcedo, K.D. & Fernandez, L. E. (2024).

Expansión de la Minería Aurífera en la Amazonía Peruana: El Riesgo del Mercurio en Loreto: Centro de Innovación Científica Amazónica (CINCIA) y Fundación para la Conservación y Desarrollo Sostenible (FCDS).

Wang, N., Ye, Z., Huang, L., Zhang, C., Guo, Y., & Zhang, W. (2022). Arsenic Occurrence and Cycling in the Aquatic Environment: A Comparison between Freshwater and Seawater. Water, 15(1), 147. https://doi.org/10.3390/w15010147

Webb, J., Coomes, O. T., Mainville, N., & Mergler, D. (2015). Mercury contamination in an indicator fish species from Andean Amazonian Rivers affected by petroleum extraction. Bulletin of Environmental Contamination and Toxicology, 95(3), 279–285. https://doi.org/10.1007/s00128-015-1588-3

Webb, J., Coomes, O. T., Ross, N., & Mergler, D. (2016). Mercury concentrations in urine of Amerindian populations near oil fields in the Peruvian and Ecuadorian Amazon. Environmental Research, 151, 344–350. https://doi.org/10.1016/j.envres.2016.07.040

Zaiontz, C. (2026) Real Statistics Using Excel. www.real-statistics.com

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