Environmental Science and Pollution Research (2022) 29:35001–35011
https://doi.org/10.1007/s11356-022-18753-7

RESEARCH ARTICLE

Essential (Cu, Zn) and nonessential (Pb, Cd) metals in the muscle of leopard groupers (*Mycteroperca rosacea*) from a mining port in the Gulf of California, Mexico: human health risk assessment

Marina Soledad Irigoyen-Arredondo[1] · **Xchel Gabriel Moreno-Sánchez**[1] · **Ofelia Escobar-Sánchez**[2,3] · **Martín Federico Soto-Jiménez**[4] · **Emigdio Marín-Enríquez**[2,3] · **Leonardo Andrés Abitia-Cárdenas**[1]

Received: 14 July 2021 / Accepted: 14 January 2022 /

Abstract

Mining activities are a current environmental issue due to heavy metal release and subsequent metal uptake by organisms. In this study, we quantified the concentrations of essential (Cu, Zn) and toxic (Cd, Pb) elements in the muscle of 248 leopard groupers, *Mycteroperca rosacea*, captured by spearfishing and free diving close to a mining district in the Gulf of California during 2014–2015. We analysed metals using high-resolution inductively coupled plasma source mass spectrometry (HR-ICP–MS). We analysed metal concentrations by fish size, sex, maturity, season, year and risk factor for human consumption. The results indicated common levels of essential elements (Cu: 11 ± 34.3 μg/g, Zn: 377 ± 1390 μg/g) in comparison with toxic elements (Cd: 0.06 ± 0.1 μg/g, Pb: 0.98 ± 1.5 μg/g). Cadmium was within the permissible limit of Mexican standards (0.5 μg/g), but lead content bordered its limit (1.0 μg/g). Heavy metal concentrations were comparable between males and females. Metal variations were not significantly correlated with sex, maturity, season or year ($p > 0.05$). The evaluation of benefits (daily mineral intake) and risks (target hazard quotients) to health indicated that these fish did not represent a risk of adverse effects to consumers within worldwide limits, while the nutritional benefits were high.

Keywords Heavy metals · Bioaccumulation · Epinephelidae · Groupers · Mining hotspot

Introduction

The presence of heavy metals in marine ecosystems is one of the main contamination issues that can lead to serious ecological, health and economic consequences (Ali and Khan 2019). Heavy metals are derived mainly from anthropogenic activities, such as the dumping of residual waters and mining wastes (Huerta-Díaz et al. 2014), which can contain persistent elements such as mercury (Hg), lead (Pb) and cadmium (Cd), which have unknown biological functions but are considered to be potentially toxic elements at even low concentrations (Ali and Khan 2019). Anthropogenic inputs related to mining waste can also contain copper (Cu) and zinc (Zn), which are essential micronutrients for physiological functions (Xu et al. 2017; Rehman et al. 2019). However, if metal content exceeds permissible limits (Zn 50 and Cu 5 μg/g w.w., UK-EEA food standards), then even essential elements could also be harmful to human health, although occurrences of acute Zn and Cu poisoning have been reported (FAO, WHO, 2001). Thus, performing

Responsible Editor: V.V.S.S. Sarma

Ofelia Escobar-Sánchez
escobars.ofelia@gmail.com

[1] Instituto Politécnico Nacional (CICIMAR-IPN), Departamento de Pesquerías Y Biología Marina. Av. IPN S/N, Col. Playa Palo de Santa Rita, La Paz, Baja California Sur. C.P. 23096, La Paz,Mexico, Mexico

[2] Universidad Autónoma de Sinaloa (UAS), Facultad de Ciencias del Mar (FACIMAR), Paseo Claussen S/N. Col. Los Pinos, CP. 82000 Mazatlán, Sinaloa, Mexico

[3] Consejo Nacional de Ciencia y Tecnología (CONACYT), Dirección de Cátedras CONACYT, Av. Insurgentes Sur 1582, Col Crédito Constructor, Del. Benito Juárez, CP. 03940 Mexico City, Mexico

[4] Unidad Académica Mazatlán, Instituto de Ciencias del Mar y Limnología, Universidad Nacional Autónoma de México (UNAM), Av. Joel Montes Camarena S/N, CP. 82040 Mazatlán, Sinaloa, Mexico

nutritional and toxicological analyses of organisms in human diet is beneficial in assessing the potential health risks that they may represent to the population, especially to children, pregnant women and lactating mothers.

Marine fish species are a key component in human diets worldwide because they contain essential amino acids, fatty acids (especially omega-3 and omega-6), protein, vitamins and minerals (Pal et al. 2018). For humans, the FAO (2017) recommends consuming fish at least 2 to 4 times per week to reduce the risk of cardiovascular diseases, diabetes and obesity. Global consumption for fish rose to above 20.5 kg *per capita* in 2016. In this sense, tunas, snappers and groupers represent 90% of the global catch (FAO 2017) and therefore, these fishes are the most widely eaten in the world.

Multiple grouper species are important in commercial fishery operations as well as in aquaculture and sport fishing activities. In Mexico, the leopard grouper, *Mycteroperca rosacea* (Streets 1877), is one of the most important species caught in the Gulf of California (Thomson et al. 2000). The annual production averaged 6360 tons/year in 2014 and 2015, with sardines, shrimp and sharks comprising the fourth component in terms of catch volume (CONAPESCA 2014). Leopard grouper meat is high-quality and carries a high price in local ($7–10 USD per kilo) and national markets.

Ecologically, leopard groupers are among the main predators in coastal environments (Craig and Hastings 2007). They occupy a high trophic level (~4.5) (Froese and Pauly 2021) with slow growth (from 15 to 21 years) (Díaz-Uribe et al. 2001), which makes them susceptible to accumulating heavy metals in tissues and organs. Overall, higher levels of heavy metals are usually associated with carnivorous and long-lived fish species (Evers et al. 2009). Despite its restricted distribution, high economic value and the scarce information on its biology, *M. rosacea* is no longer designated as "vulnerable" by the International Union for the Conservation of Nature (IUCN) and has a current designation of "least concern" (Erisman and Craig 2018). Although there have been no reported changes in leopard grouper populations over the past 30 years, enforcement may be needed due to intense fishing pressure (Erisman and Craig 2018).

Fishing for leopard grouper occurs most intensely along the Gulf of California coastlines; however, consumption of their meat occurs both locally and nationally. The primary objective of this study was to evaluate metal concentrations in leopard grouper tissues as a function of fish biology (size, sex and maturity) and collection time (season and year). A second objective was to assess the potential human health benefits or risks related to concentrations of Cu, Pb, Cd and Zn in the muscle tissue of the leopard grouper *M. rosacea*.

Materials and methods

Study area and sample collection

We obtained specimens of *Mycteroperca rosacea* in the port of Santa Rosalía (27° 20.353′ N; 112° 15.797′ W), Baja California Sur, in the Gulf of California, Mexico (Fig. 1). Since 1885, this port has been involved in the copper extraction industry through the French mining company "Compagnie du Boleo, S.A.". Currently, the company operates under the name "Minera y Metalúrgica del Boleo S.A. de C.V." (Huerta-Díaz et al. 2014). An estimated three million tons of slag has accumulated at mine sites, and undetermined amounts have entered the gulf's marine environments (Shumilin et al. 2013; Huerta-Díaz et al. 2014). In addition to the mining industry, Santa Rosalía is a primary port for fishing and tourism vessels, cargo and passenger ferries, and small boats (Huerta-Díaz et al. 2014). Therefore, the marine environment is potentially polluted and marine organisms that inhabit the area, including the leopard grouper, may contain heavy metals.

We captured organisms monthly (from March 2014 to May 2015) by spearfishing while free diving to obtain a good representation of varied sizes. We stored specimens on ice until processing at the Fish Ecology Laboratory at CICIMAR-IPN, where we recorded total length (TL, cm) and weight (g). Sex was identified by direct observation of the gonads and later corroborated with histological analyses (Nikolsky 1963; Pérez-Olivas et al. 2018). We followed the four stages of maturity as reported by Pérez-Olivas et al. (2018).

We caught a total of 345 M. *rosacea* individuals, ranging in size from 21 to 74 cm total length; 93 specimens were male, and 185 were female. Our specimens included a total of 15 bisexual immature organisms, as well as 52 individuals for which we were unable to determine sex even via histological analysis, all of which we excluded from the comparative analyses of sex and stage of maturity.

We grouped data by sex (males and females), maturity stage (stage 1, stage 2, stage 3 and stage 4) and size (small: < 36 cm, medium: > 36 cm, and ≤ 51 cm, large: > 51 cm). We defined seasonality according to temperature records for the study period obtained from MODIS-AQUA satellite images with 1.1 km resolution. We recorded anomalies based on the annual average of 23 °C (Moreno-Sánchez et al. 2019). We assigned months with positive temperature anomalies to the warm season and assigned negative anomalies to the cold season.

We dissected fish specimens in the laboratory. We removed the skin and collected 5.0 g of muscle tissue from the anterior dorsal part of each individual. We conducted the extraction of muscle samples with care to avoid contamination and exposure. We washed scalpels with Milli-Q water during the entire process. We tagged each sample, placed them in plastic bags and stored them frozen at – 20 °C.

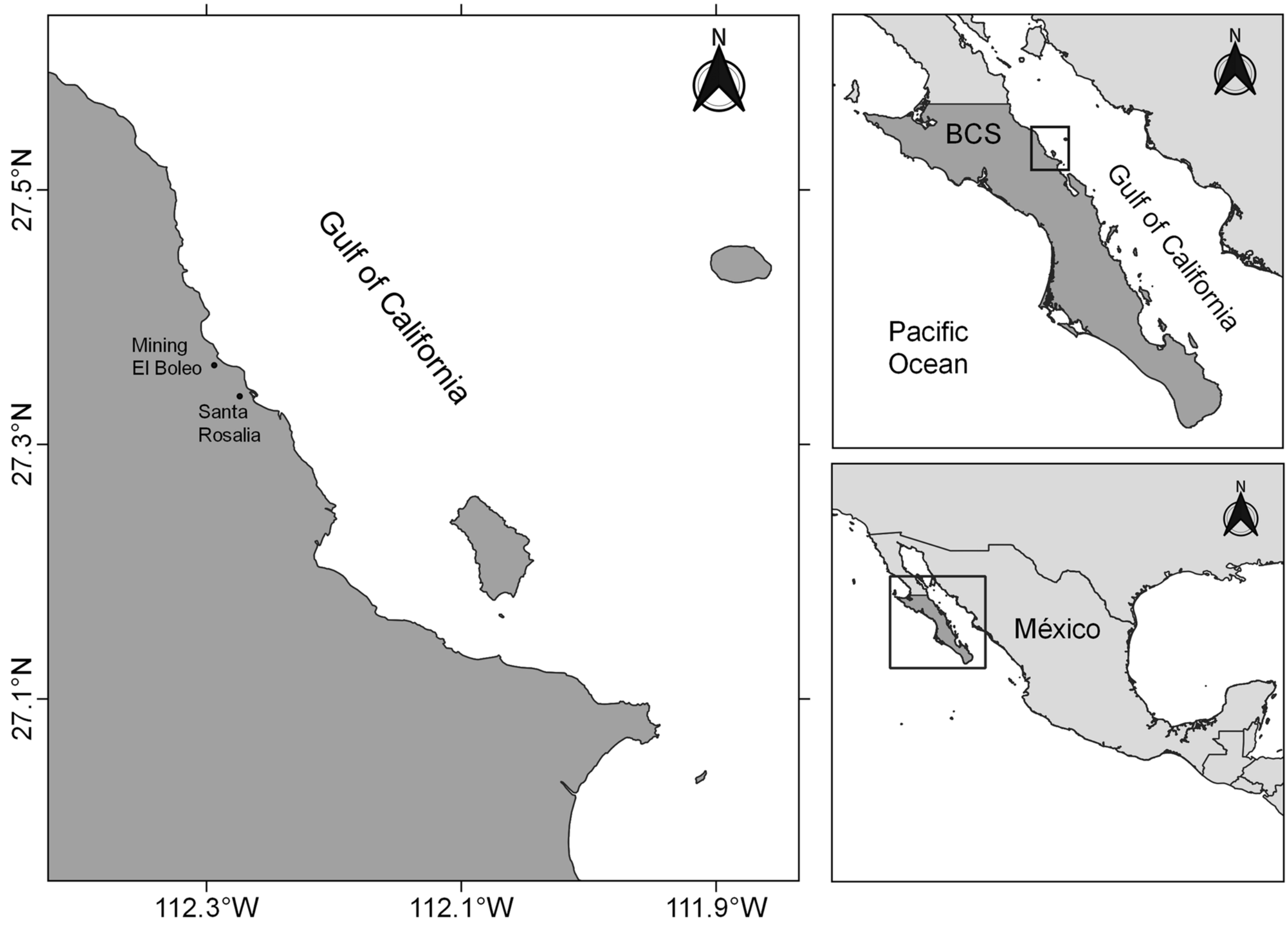

Fig. 1 Geographic location of the port of Santa Rosalía, Baja California Sur, Mexico

Heavy metal analysis

We lyophilized muscle tissue samples at 0.120 mBar pressure and – 40 °C for 72 h (Labconco, FreeZone 2.5). We calculated the water content (%) by weighing the differences between fresh frozen and dried samples. The dried samples were ground using an agate mortar, homogenized and packed into trace metal-cleaned plastic vials.

Then, we sent 248 composite muscle samples to the Stable Isotope Laboratory at the ICMYL-UNAM at Mazatlán for elemental analysis. We processed samples and analysed in HEPA-filtered air (Class 1000) in a trace metal-free laboratory using high-purity reagents (trace metal grade) and water (18 MW cm^{-1}; Milli-Q academic). We digested aliquots of fish muscle, blanks and certified reference material in Teflon vials (Savillex) with 10 mL concentrated nitric acid (HNO_3). We then placed the containers on a mod-block unit (120 °C) for 4 h. After digestion, we transferred samples to polyethylene vials and diluted with Milli-Q water to a known volume (25 mL).

We conducted analyses for metals using a Thermo Scientific Element XR magnetic sector high-resolution inductively coupled plasma source mass spectrometer (HR-ICP–MS) (Soto-Jiménez et al. 2008). We ascertained the accuracy of the analyses with concurrent processing of certified reference material (CRM) composed of Dog-Fish muscle (DORM-3) from the Institute for National Measurement Standards of the National Research Council Canada. The recovery values of CRM for Cd were 92%, Cu 94%, Pb 88% and Zn 92%. The detection limits were < 6 ng g^{-1} dry weight for Cd, < 10 ng g^{-1} for Pb and < 20 ng g^{-1} for Cu and Zn. We calculated concentrations of metals in fish in μg/g dry weight but reported as averages ± standard deviations in μg/g wet weight.

Toxicological evaluation

To establish the amount of leopard grouper fillet that the human population could consume without a health risk, the MPCF (maximum possible consumption of fish meat (containing Cd or Pb) per week) was calculated using the following formula: $MPCF = PTWI/MTj$, where PTWI is the provisional tolerable weekly intake of Cd and Pb, in μg week^{-1} kg^{-1} of body weight (Cd: 2.5 μg kg^{-1} w.w.; Pb:

25 µg kg^{-1} w.w.; EFSA, 2012), and MT is the metal concentration (µg/g, w.w.) in muscle tissue of leopard grouper. We estimated the calculation assuming an average weight among the general population (70 kg), considering women (60 kg, pregnant and lactating) and children (16 kg, 4–6 years old). Additionally, we used average weights for the Santa Rosalía population (75 kg for men, 69 kg for women and 18 kg for 4-year to 6-year-old children) (INEGI 2015). We also used these average weights for additional evaluations.

The daily mineral intake of essential elements (Cu, Zn) was calculated based on the consumption recommended by the Institute of Medicine of the National Academies of the United States (www.iom.edu) using the following equation: $DMI = C * 100/RDI$, where DMI = daily mineral intake of essential elements, C = Cu or Zn concentration in 100 g of fresh fish weight and RDI = recommended daily intake, estimated as safe and adequate for each group in the population. CuRDI: men, women and children = 900 µg/day, pregnant and lactating women = 1000 µg/day; ZnRDI: men, women, pregnant and lactating women = 40 µg/day, children = 34 µg/day. We estimated these values for a healthy population.

Additionally, we calculated the potential health risk due to harmful effects from long-term leopard grouper consumption (e.g. months or years) as the target hazard quotient, where high THQ values (> 1) would represent a health risk. We calculated THQ as follows:

$$THQ = \frac{EF * ED * FIR * C}{RfD * BW * AT}$$

In this equation, C is the concentration of Cu, Pb, Cd or Zn (µg/g); EF is the exposure frequency (days/year); ED is the exposure duration (years/time); FIR is the fish intake rate (g/day); RfD is the daily fish intake rate (g/day); BW is the average body weight of the human population (kg); and AT is the average exposure time (days). We obtained all parameters except C, FIR and BW from actual data for the Santa Rosalía, BCS, Mexico population. We obtained the remaining data used in the formula, shown in Table 1, from the FAO (2017), US EPA (2015) and Yi et al. (2011).

Because heavy metal (Cu, Pb, Cd and Zn) interactions can cause multiple effects (Gu et al., 2017), we considered the added effect of these elements in the THQ, as recommended by Chien et al. (2002) and Gu et al. (2017), as shown in the following equation:

$$\text{Total}THQ(TTHQ) = \sum THQ_{\text{Cu,Pb,Cd,Zn}}$$

Data analysis

We conducted simple linear regression (LR) analysis to assess the association between the concentration of each heavy metal and the size of leopard groupers. We separated the database into categories (sex, maturity stages and season), and fitted an LR of the heavy metal concentration as a function of size for each heavy metal and each category. We used this analysis to evaluate the hypothesis that the b coefficient of the LR model was zero (e.g. there was no association between heavy metal concentration and size). We performed all analyses using packages found in R (R Core Team 2017).

Results

Heavy metal concentrations in muscle tissue

Table 2 shows a summary of the heavy metal concentrations in the muscle of leopard grouper *M. rosacea* caught in Santa Rosalía (average ± SD, maximum and minimum) and a comparative analysis of sex, maturity stage and total length. The sex groups, males, females and hermaphrodites showed comparable ranges for all metals (Table 2). Because of the comparable values and the high intravariability among sex groups, we observed no significant differences.

Heavy metal concentrations in maturity stages were stage 1 (Cu: 18.1 ± 58.4 µg/g; Zn: 588 ± 2394 µg/g; Cd: 0.1 ± 0.2 µg/g; Pb: 1.5 ± 2.4 µg/g), stage 2 (Cu: 16.8 ± 55.6 µg/g; Zn: 517.9 ± 2256 µg/g; Cd: 0.1 ± 0.2 µg/g; Pb: 1.5 ± 2.4 µg/g), stage 3 (Cu: 13.8 ± 56.7 µg/g; Zn: 439.2 ± 2323 µg/g; Cd: 0.1 ± 0.2 µg/g; Pb: 1.4 ± 2.3 µg/g) and stage 4 (Cu: 14.1 ± 58.1 µg/g; Zn: 447.3 ± 2362 µg/g; Cd: 0.1 ± 0.2 µg/g; Pb: 1.6 ± 2.5 µg/g). There were no significant differences between metal levels in maturity stages.

Table 1 Parameters and values used for the THQ formula for each heavy metal

Factor	Definition	Unit	Value	Reference
EF	Exposure frequency	Days/year	365	Yi et al. (2011)
ED	Duration	Years	78	Yi et al. (2011)
FIR	Fish intake rate	g/day	32.8	
RfD	Reference dose	µg/kg/day	1.0E^{-01} (Cd), 2.0E^{+01} (Pb), 4.0E^{+01} (Cu), 3.0E^{+02} (Zn)	US EPA (2015)
BW	Average weight	kg	70 ± 75	WHO; INEGI (2015)
AT	Average exposure time	Days	365*78 = 28.470	Yi et al. (2011)

Table 2 Heavy metal concentrations (mean ± SD; µg/g wet weight) in *Mycteroperca rosacea* muscle in a mining port in the Gulf of California, Mexico

Category		*n*	Cu	Zn	Cd	Pb
	Overall	248	11.6 ± 34.3 (0.01–361)^{c}	377.3 ± 1389.9 (0.02–13,165)^{c}	0.06 ± 0.13 (0.001–1.13)	0.98 ± 1.56 (0.03–9.8)^{b}
Sex						
	Females	132	12.7 ± 39.9 (0.01–361)^{c}	433.8 ± 1628.5 (0.02–13,165)^{c}	0.05 ± 0.12 (0.001–0.69)	1.06 ± 1.71 (0.03–8.9)^{a,b}
	Males	70	13.6 ± 33.6 (0.1–226)^{c}	448.8 ± 1348 (0.01–9442)^{c}	0.08 ± 0.2 (0.01–1.1)	0.84 ± 1.0 (0.02–9.8)^{b}
	Hermaphrodites	15	7.7 ± 7.7 (0.02–20)^{c}	164.7 ± 219.9 (0.1–807)^{c}	0.07 ± 0.1 (0.001–0.3)	0.79 ± 1.3 (0.02–5.3)^{b}
Size						
	Small	129	12 ± 34 (0.2–361)^{c}	385 ± 1644 (0.1–13,165)^{c}	0.06 ± 0.1 (0.01–1.1)	0.98 ± 1.6 (0.1–9.8)^{b}
	Medium	99	11 ± 32 (0.01–361)^{c}	328 ± 1269 (0.02–13,165)^{c}	0.06 ± 0.1 (0.01–0.7)	1.0 ± 1.5 (0.02–9.8)$^{a, b}$
	Large	20	7 ± 32 (0.2–90)^{c}	246 ± 1330 (0.8–6901)^{c}	0.03 ± 0.07 (0.01–0.1)	0.86 ± 1.4 (0.05–2.7)^{b}
Maturity stage						
	Maturity stage 1	141	18.1 ± 58.4 (0.3–283)^{c}	588 ± 2394 (2.3–12,006)^{c}	0.1 ± 0.2 (0.01–0.8)^{a,b}	1.5 ± 2.4 (0.07–15.4)^{a,b}
	Maturity stage 2	47	16.8 ± 55.6 (0.3–123)^{c}	517.9 ± 2256 (6.0–5767)^{c}	0.1 ± 0.2 (0.01–1.3)^{a,b}	1.5 ± 2.4 (0.06–11.0)^{a,b}
	Maturity stage 3	76	13.8 ± 56.7 (0.3–664)^{c}	430.2 ± 2323 (3.7–24,197)^{c}	0.1 ± 0.2 (0.01–0.9)^{a,b}	1.4 ± 2.3 (0.06–6.5)^{a,b}
	Maturity stage 4	8	14.1 ± 58.1 (0.6–132)^{c}	447.3 ± 2362 (12.2–2231)^{c}	0.1 ± 0.2 (0.02–0.1)^{a,b}	1.6 ± 2.5 (0.05–1.7)^{a,b}
Season						
	Warm season	80	2.0 ± 3.0 (0.2–23)	50 ± 66 (0.8–411)^{c}	0.01 ± 0.03 (0.02–0.11)	1.0 ± 2.0 (0.05–9.8)^{a,b}
	Cold season	168	16 ± 35 (0.1–361)^{c}	539 ± 1412 (0.1–13,165)^{c}	0.11 ± 0.15 (0.01–1.1)^{a,b}	1.0 ± 1.6 (0.02–8.9)^{a,b}
Year						
	2014	180	8.8 ± 31.5 (0.17–361)^{c}	251 ± 1239 (0.1–13,165)^{c}	0.08 ± 0.2 (0.02–1.1)	0.97 ± 1.6 (0.03–9.9)^{b}
	2015	68	26 ± 38.4 (0.2–205)^{c}	867 ± 1499.7 (5.1–8702)^{c}	0.2 ± 0.3 (0.1–1.1)^{b}	1.5 ± 1.9 (0.1–1.9)^{a,b}

[a] Values above recommended limits set by the official Mexican norm NOM-242-SSA1-2009 (Cd 0.5 and Pb 1.0 µg/g w.w.)

[b] US-EPA, FDA criterion, surpassing established limits of 0.5 for Cd and 0.5 for Pb

[c] United Kingdom norm (UK-EEA food standards) of Zn 50 and Cu 5 µg/g w.w

Regarding size, the metal levels were as follows: small fish (Cu: 12 ± 34 µg/g; Zn: 385 ± 1644 µg/g; Cd: 0.06 ± 0.1 µg/g; Pb: 0.98 ± 1.6 µg/g), then medium-sized fish (Cu: 11 ± 32 µg/g; Zn: 328 ± 1269 µg/g; Cd: 0.06 ± 0.1 µg/g; Pb: 1.0 ± 1.5 µg/g) and large specimens presented lower concentrations (Cu: 7.0 ± 32 µg/g; Zn: 246 ± 1330 µg/g; Cd: 0.03 ± 0.07 µg/g; Pb: 0.86 ± 1.4 µg/g). We observed no significant differences among the size groups.

A comparative analysis related to the collection time showed that the heavy metal concentrations in organisms collected in 2015 (Cu: 26 ± 38.4 µg/g; Zn: 867 ± 1499 µg/g; Cd: 0.2 ± 0.3; Pb: 1.5 ± 1.9 µg/g) were significantly higher ($p < 0.05$) than those collected in 2014 (Cu: 8.8 ± 31.5 µg/g; Zn: 251 ± 1239 µg/g; Cd: 0.08 ± 0.2 µg/g; Pb: 0.97 ± 1.6 µg/g). In addition, significant differences ($p < 0.05$) were observed for Cu, Zn and Cd between the warm (Cu: 2.0 ± 3.0 µg/g; Zn: 50 ± 66 µg/g; Cd: 0.01 ± 0.03 µg/g) and cold seasons (Cu: 16 ± 35 µg/g; Zn: 539 ± 1412 µg/g; Cd: 0.11 ± 0.15 µg/g) but not for lead (warm: 1.0 ± 2.0 µg/g; cold: 1.0 ± 1.6 µg/g).

The results of the fitted simple linear regression (LR) suggested that the association between heavy metal concentration in muscle and the size of leopard groupers was weak (low R^2 values) and not significant ($p\ (b = 0) > 0.05$ in all cases) (Table 3).

A comparison of metal concentrations found in the grouper muscle samples showed that the essential elements (Cu = 11.61 ± 34.36 µg/g and Zn = 377.33 ± 1389.98 µg/g) presented global values that exceeded the norms set by the UK (UK-EEA food standards Cu: 5.0 µg/g; Zn: 50 µg/g), whereas Cd, a nonessential element (Cd = 0.06 ± 0.13 µg/g vs. Cd = 0.05 µg/g), was within the ranges established by NOM-242 (Table 2). In the case of Pb, the global average borders the limit established by NOM-242. In fact, almost half of the samples ($n = 114$, 46%) were above the limit of 1 µg/g.

Ecotoxicological evaluation

According to the general calculations of the maximum possible consumption of fish meat per week (MPCF) for Cd values, we suggest that children under 6 years can consume fish fillets of up to 667 g per week and others can consume up to 2000 g of leopard grouper. However, Pb values indicated that the frequency of leopard grouper consumption should decrease (Table S1). The average values of the risk coefficient (THQ_{Cu}: 0.1 ± 0.3, THQ_{Pb}: 0 ± 0.1, THQ_{Cd}: 0.3 ± 1.4, THQ_{Zn}: 0.2 ± 0.6)

Table 3 Coefficient values of the linear regression of variations by sex, maturity stages and season in the muscle of leopard grouper *Mycteroperca rosacea* in Santa Rosalía, BCS,Mexico

Variables	Linear regression coefficients					
	n	R^2	b	a	$p\ (a=0)$	$p\ (b=0)$
Cu						
F	132	0.004	0.3	2,047,030	1	0.46
M	69	0.01	0.4	−2,975,734	0.87	0.36
Maturity stage 1	141	0.01	0.5	−1,018,392	0.97	0.45
Maturity stage 2	47	0.02	−0.48	26,628,406	0.02	0.14
Maturity stage 3	76	0.01	0.6	−11,830,348	0.74	0.43
Maturity stage 4	8	0.14	2688	−76,258,327	0.48	0.40
Cold	148	0.01	0.5	−2,897,376	0.85	0.19
Warm	47	0.05	−0.1	6,542,092	0.01	0.12
Pb						
F	132	0.0005	−0.005	13,403,743	0.07	0.79
M	69	0.04	0.02	−0.1501317	0.75	0.07
Maturity stage 1	141	0.007	−0.02	19,128.434	0.03	0.39
Maturity stage 2	47	0.105	0.07	−18,344,799	0.24	0.06
Maturity stage 3	76	0.04	0.02	−0.1766029	0.77	0.13
Maturity stage 4	8	0.11	0.03	−0.7844367	0.62	0.45
Cold	148	0.0004	−0.003	11,716,741	0.03	0.80
Warm	47	0.01	0.02	−0.1538668	0.90	0.42
Cd						
F	132	0.02	−0.002	0.138755835	0.002	0.06
M	69	0.005	0.001	0.010781516	0.92	0.54
Maturity stage 1	141	0.03	−0.002	0.158315518	0.002	0.05
Maturity stage 2	47	0.001	0.001	0.088152186	0.74	0.83
Maturity stage 3	76	0.003	0.0005	0.007955513	0.89	0.70
Maturity stage 4	8	0.14	0.002	−0.077131024	0.49	0.40
Cold	148	0.001	−0.0006	0.100902619	0.10	0.69
Warm	47	0.02	−0.0005	0.044550624	0.02	0.27
Zn						
F	132	0.01	252,802,895	−48,738,201	0.43	0.13
M	69	0.009	151,811,566	−15,627,183	0.83	0.42
Maturity stage 1	141	0.008	−127,235,772	74,047,734	0.12	0.35
Maturity stage 2	47	0.005	87,707,420	9,110,244	0.91	0.67
Maturity stage 3	76	0.01	302,079,514	−62,109,127	0.65	0.37
Maturity stage 4	8	0.13	453,892,443	−129,630,397	0.48	0.41
Cold	148	0.02	297,236,154	−53,587,711	0.38	0.07
Warm	47	0.02	0.69	1,298,858	0.62	0.31

showed there was no risk from leopard grouper ingestion; however, the maximum range of THQ_{Cd} values could surpass established limits (> 1). In contrast, the suggested amounts of essential elements (Cu and Zn) were higher for the three human population groups (children, women and men).

The benefits that consumption of this fish provide for vulnerable groups in the population (children, pregnant and lactating women) indicated that each 100 g of leopard grouper fillet represented over 1% Cu and 100% Zn. The percentages of Cu daily mineral intake oscillated between 1.2 and 1.3, while the percentages of Zn daily mineral intake ranged from 943 to 1110.

Discussion

The leopard grouper *Mycteroperca rosacea* is one of the main predatory species on rocky reefs (Thomson et al. 2000; Moreno-Sánchez et al. 2019). Due to its carnivorous habits and slow growth (Díaz-Uribe et al. 2001), it can be susceptible to bioaccumulating heavy metals, as occurs with other species that share these characteristics, such as *Scomberomorus sierra*, *Nematistius pectoralis*, *Caulolatilus princeps* and *Lutjanus colorado* (Frías-Espericueta et al. 2010; Ruelas-Inzunza et al. 2010, 2014). However, Cd concentrations (0.06 µg/g) were below the limit set by the Mexican norm

NOM-242, whereas Pb concentrations found in *M. rosacea* muscle tissue (0.98 µg/g) were on average close to the limit set by the Mexican norm (Pb: 1.0 µg/g; Cd: 0.5 µg/g). The average values of essential metals (Cu: 11.61 ± 34.36 µg/g; Zn: 377.33 ± 1389.98 µg/g) were well above the maximum criteria allowed by international regulations (UK-EEA food standards Cu: 5.0 µg/g; Zn: 50 µg/g).

Previously reported levels of Cd (0.2 µg/g) and Pb (2.5 µg/g) have been up to three times higher than those recorded here for *M. rosacea* in other commercially important species in Sinaloa, Mexico (*S. sierra*, *C. princeps* and *L. colorado*). Coastal ecosystems in Sinaloa have a significant anthropogenic influence with raw or partially processed effluents from aquaculture, agriculture, the food processing industry, urban wastewater and fisheries converge (Frías-Espericueta et al. 2010; Ruelas-Inzunza et al. 2014). Concentrations of Cu, Zn, Pb and Cd above the limits established in the sediment quality criteria (Cu: 3860, Zn: 2600, Pb: 240, Cd: 240 mg/kg) have occurred in the Central Gulf of California (in Santa Rosalía). Cooper mining activities in the Santa Rosalía maritime port, from the beginning of the nineteenth century to the present, are the most important source of heavy metals to the adjacent coastal region (Jonathan et al. 2016). Although specific cases of inputs of contaminants are fundamental in explaining the presence of heavy metals in organisms (Zhang et al. 2017; Ali and Khan 2019), the concentrations of Pb and Cd found in *M. rosacea* do not reflect those inputs. However, the concentrations of essential elements such as Cu (11.6 µg/g) reported for *M. rosacea* in the Gulf of California were five times higher than those reported in Sinaloa for other fish such as *L. colorado* (Cu: 2.1 µg/g).

Few studies have investigated heavy metals in serranid species (Table 3), and these studies reported low metal concentrations in comparison with our study. However, two studies indicated elevated levels of Cd in *Mycteroperca fusca* (2.54 ± 10.3 µg/g; Franco-Fuentes et al. 2021) and *Mycteroperca olfax* (10.70 ± 7.93 µg/g; Lozano et al. 2009). The authors attributed these levels to differences in age, size, metabolic activity and feeding habits. In this sense, several studies reported that organisms that feed on invertebrates show lower heavy metal levels than those that include a greater proportion of fish in their diet (Escobar-Sánchez et al. 2016; Murillo-Cisneros et al. 2018; Sujitha et al. 2019). *Mycteroperca rosacea* is a predator that feeds primarily on the euphausiid *Nyctiphanes simplex*, which comprises 65% of the diet, in terms of relative importance (Moreno-Sánchez et al. 2019). Therefore, we would expect that due to the type of feeding shown by *M. rosacea* its average heavy metal concentrations would be at the limit (Pb) and/or below the limit (Cd) set by NOM-242-SSA-2009.

Other variables, such as size and sex, could affect the bioaccumulation of heavy metals (Xia et al., 2019). For example, elements such as Hg and Cd have shown a positive relationship with fish size (Tremain and Adams 2012; Ruelas-Inzunza et al. 2014), where there were greater heavy metal concentrations at greater fish sizes, as reported for other grouper species (*Epinephelus*, *Mycteroperca* and *Cephalopholis*) (Tremain and Adams 2012). However, this correlation was not related to growth (in size, age or weight) for other heavy metals such as Pb, Zn and Cu (García-Hernández et al. 2007; Rodrigues et al. 2018; Xia et al. 2019). In our study, there was no evident relationship between total length and the analysed heavy metals. García-Hernández et al. (2007) showed that the lack of correlation between size and heavy metal concentrations (Hg, specifically) can be related to different fish species feeding on the same food components.

Nyctiphanes simplex is the main prey for *M. rosacea* in Santa Rosalía; however, this grouper can vary the proportion of food items in its diet according to size (Moreno-Sánchez et al. 2019). For example, small-sized grouper (< 36 cm; *n*: 129) fed exclusively on euphausiids (*N. simplex*), whereas medium-sized fish (> 36 cm < 51 cm; *n*: 99) had a mixed diet (invertebrates and fish), and large organisms (> 51 cm; *n:* 20) consumed a greater proportion of fish (*S. sagax*, *Microlepidotus inornatus*, *Chromis atrilobata*) (Moreno-Sánchez et al. 2019). As mentioned previously, this would imply that large organisms would show greater heavy metal concentrations (Murillo-Cisneros et al. 2018). However, although differences in the diet do reflect heavy metal concentrations by size (small, medium and large), the greatest heavy metal concentrations were recorded in the small and medium-sized organisms (see Table 2) rather than in the largest. Sujitha et al. (2019) reported that in different crustacean species (e.g. *Panulirus interruptus*, *Penaeus stylirostris*), high Zn (> 80 µg/g) and Cu (> 45 µg/g) levels occurred, which could explain the presence of greater quantities of those elements in smaller *M. rosacea*.

The occurrence of greater Cu and Zn concentrations in small-sized fish could be due to small individuals showing accelerated growth in their first years of life (1–3 years), as these elements are required for critical physiological processes. Moreover, the elimination rate of toxic metals is more efficient (Rajeshkumar and Li 2018). Estimates for size at first maturity of *M. rosacea* are 40.7 cm total length (Pérez-Olivas et al. 2018), which coincides with essential element concentrations being greater in small and medium-sized fish. That is, we would expect that groupers of this size would have higher heavy metal levels because Cu and Zn are important micronutrients for gonad maturation and are necessary to carry out reproduction successfully (Jezierska et al. 2009). We suggest that the low Pb and Cd levels recorded could be due to more efficient elimination at those sizes (Yi and Zhang 2012), at least in *M. rosacea*.

Elevated levels of Pb and Cd at all maturity stages suggest increased metabolic activity and high lipid content of the gonads that stimulate rapid accumulation of lipophilic metallic species and are associated with metallothionein synthesis in the liver (El-Greisy and El-Gamal 2015). Metallothionein proteins bind to metals, and Cd forms a nontoxic complex, which tissues retain, resulting in bioaccumulation. This phenomenon shows that stage of sexual maturity plays a role in understanding the bioavailability of metals and detoxification of both essential and nonessential metals (Hemmadi 2016).

Compared with reports for the El Niño events of 1997 and 1998, the El Niño phenomenon of 2015 was the most intense event recorded, with temperatures over 0.76° higher than those of the previous record (Pérez-Olivas et al. 2018). Because of this, there was a difference of 2.2 °C between 2014 and 2015. This temperature difference coincided with greater metal concentrations in 2015 (Cu: 26 μg/g, Zn: 867 μg/g, Cd: 0.2 μg/g, Pb: 1.5 μg/g) than in 2014 (Cu: 8.8 μg/g, Zn: 251 μg/g, Cd: 0.08 μg/g, Pb: 0.97 μg/g). These increases in heavy metal concentrations coincide with a report by Huerta-Díaz et al. (2014) for the same study area regarding high heavy metal levels resulting from the mixing and removal of particulate materials in marine sediments caused by natural phenomena such as hurricanes and storms.

In 2014, hurricane "Odile" impacted Baja California Sur (CONAGUA 2014) in the months categorized as the warm season, coinciding with enrichment in heavy metals during the previously mentioned phenomenon. Therefore, the heavy metal enrichment observed in 2015 could reflect the impact of the hurricane entraining heavy metals through pluvial precipitation and temporary streams flowing into the port. Other environmental and industrial activities in Santa Rosalía could be involved in increased heavy metal concentrations. Such increases have occurred as reported in studies on heavy metals in north-western Mexico (Frías-Espericueta et al. 2010; Ruelas-Inzunza et al. 2010; 2014).

Heavy metals are a potential problem in areas close to coasts and constitute a human health risk. However, there is currently a discrepancy between recommendations by public health sectors (FAO 2017) and studies that advise reducing the consumption of fish fillet. Additionally, fish consumption may be greater than we assumed because the frequency of fish consumption in coastal communities is often greater than reported.

In this study, a consumption of 700 g does not represent a risk to health. However, the frequency of leopard grouper consumption by the population of Santa Rosalía was greater than what we recommend (CONAPESCA 2014). Essential elements such as Cu and Zn are required for the correct absorption of vitamins B_6, B_{12}, C and A, among others, especially in vulnerable groups (children, pregnant women and lactating women). According to daily mineral intake values, the *M. rosacea* fillet is generally recommended and beneficial to the population. This fish offers high nutritional value, and it meets worldwide levels (FAO 2017) and is even higher than what has been reported for other fish in north-western Mexico (Frías-Espericueta et al. 2010).

The risk factor (THQ) showed no adverse long-term effects, whereas we advise caution for Cd due to the maximum values obtained. In the present study, we suggest continuous monitoring of Cd levels to more deeply evaluate the THQ and the consideration of later years because estimated values correspond to 2014 and 2015.

Conclusion

This is the first study focusing on heavy metals in *Mycteroperca rosacea*. The results on metal concentrations suggest that, although the samples of leopard groupers (*M. rosacea*) come from an area adjacent to a mining district, "El Boleo" in Santa Rosalía, Mexico, no essential metals (Cd and Pb) were below the limit set by the EPA, FDA and Mexican norms (NOM-242). We need further monitoring for Pb because its average concentration was close to the limit set by the Mexican norm. The leopard grouper did not represent adverse effects to the consumer; in contrast, the nutritional benefits were high. Enrichment of heavy metals during the warm season may occur as a result of natural phenomenon (e.g. hurricanes). *Mycteroperca rosacea* continues to be marketed; therefore, it is important to know the ingestion rate of this species in Mexico to understand metal impacts on human populations.

Supplementary information.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11356-022-18753-7.

Acknowledgements We would like to acknowledge the fisherman from Santa Rosalía, Mexico. Technical assistance was given by Karla Sánchez Osuna. The authors are grateful for economic support obtained from scholarships provided by SIP-IPN (20150949, 20160319, 20170476, 20181071) projects and the research project Problemas Nacionales (CONACYT 248708). MSIA is thankful for economic support derived from CONACyT and BEIFI-IPN. XGMS and LAAC are thankful for support obtained from COFAA and EDI scholarships. OES and EME thank CONACYT for financial support through the "Cátedras-CONACYT/2137" project. All the authors are grateful to the "Sistema Nacional de Investigadores (SNI)".

Author contribution Marina S. Irigoyen-Arredondo: conceptualization, data analysis, writing—original draft preparation. Xchel G. Moreno-Sánchez: conceptualization, visualization, investigation. Ofelia Escobar-Sánchez: funding acquisition, project administration, data curation, writing—reviewing and Editing. Martín F. Soto-Jiménez: data curation, writing—reviewing and editing. Emigdio Marín-Enríquez: software. L. Andrés Abitia-Cárdenas: conceptualization, supervision, investigation, funding acquisition.

Funding This study is supported by the CONACYT (CONACYT 248708) and Intituto Politécnico Nacional (20150949, 20160319, 20170476, 20181071).

Availability of data and materials Not applicable.

Declarations

Ethics approval and consent to participate Not applicable. This manuscript does not contain any studies with human participants or animals performed by any of the authors.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

Abdul-Wahab SA, Al-Husaini IS, Rahmalan A (2013) Using grouper fish as bio-indicator of Cd, Cu, Pb and V in the vicinity of a single buoy mooring (SBM3) at Mina Al Fahal in the Sultanate of Oman. Bull Environ Contamin Toxicol 91(6):684–688. https://doi.org/10.1007/s00128-013-1126-0

Agah H, Leermakers M, Elskens M, Fatemi SMR, Baeyens W (2009) Accumulation of trace metals in the muscle and liver tissues of five fish species from the Persian Gulf. Environ Monit Assess 157(1):499–514. https://doi.org/10.1007/s10661-008-0551-8

Ali H, Khan E (2019) Trophic transfer, bioaccumulation, and biomagnification of non-essential hazardous heavy metals and metalloids in food chains/webs Concepts and implications for wildlife and human health. Hum Ecol Risk Assess 25(6):1353–1376. https://doi.org/10.1080/10807039.2018.1469398

Al-Sayed HA, Al-Saad J, Madany IM, Al-Hooti D (1996) Heavy metals in the grouper fish Epinephelus coioides from the coast of Bahrain: an assessment of monthly and spatial trends. Int J Environ Stud 50(3–4):237–246. https://doi.org/10.1080/00207239608711060

Alturiqi AS, Albedair LA (2012) Evaluation of some heavy metals in certain fish, meat and meat products in Saudi Arabian markets. Egypt J Aquat Res 38(1):45–49. https://doi.org/10.1016/j.ejar.2012.08.003

Chien LC, Hung TC, Choang KY, Yeh CY, Meng PJ, Shieh MJ, Han BC (2002) Daily intake of TBT, Cu, Zn, Cd and As for fishermen in Taiwan. Sci Total Environ 285:177–185. https://doi.org/10.1016/S0048-9697(01)00916-0

CONAGUA (2014) Comisión Nacional del Agua. Declaratoria de Desastre Natural por la ocurrencia del Huracan "Odile" del 14 al 15 de septiembre del 2014, en 5 municipios del Estado de Baja California Sur. http://files.conagua.gob.mx/transparencia/PNH2014.pdf.

CONAPESCA (2014) Comisión Nacional de Pesca y Acuacultura. Anuario Estadística de Pesca. http://www.conapesca.sagarpa.gob.mx/wb/cona/anuario_2014

Craig MT, Hastings PA (2007) A molecular phylogeny of the groupers of the subfamily Epinephelinae (Serranidae) with a revised classification of the Epinephelini. Ichth Res 54(1):1–17. https://doi.org/10.1007/s10228-006-0367-x

da Silva CA, Garcia CA, de Santana HL, de Pontes GC, Wasserman JC, da Costa SS (2021) Metal and metalloid concentrations in marine fish marketed in Salvador, BA, northeastern Brazil, and associated human health risks. Reg Stud Mar Sci 43:101716. https://doi.org/10.1016/j.rsma.2021.101716

Díaz-Uribe JG, Elorduy-Garay JF, González-Valdovinos MT (2001) Age and growth of the leopard grouper, *Mycteroperca rosacea*, in the southern Gulf of California, Mexico. Pac Sci 55:171–182. https://doi.org/10.1353/psc.2001.0012

EFSA (2012) Cadmium dietary exposure in the European population. EFSA J 10:2551. https://doi.org/10.2903/j.efsa.2012.2551

El-Greisy ZA, El-Gamal AHA (2015) Experimental studies on the effect of cadmium chloride, zinc acetate, their mixture and the mitigation with vitamin C supplementation on hatchability, size and quality of newly hatched larvae of common carp, Cyprinus carpio. Egypt J Aquat Res 41:219–226. https://doi.org/10.1016/j.ejar.2015.03.007

Escobar-Sánchez O, Ruelas-Inzunza J, Moreno-Sánchez XG, Romo-Piñera AK, Frías-Espericueta MG (2016) Mercury concentrations in Pacific angel sharks (Squatina californica) and prey fishes from Southern Gulf of California, Mexico. Bull Environ Contam Toxicol 96:15–19. https://doi.org/10.1007/s00128-015-1708-0

Erisman B, Craig MT (2018) *Mycteroperca rosacea*. The IUCN Red List of Threatened Species 2018: e.T14053A100466656. https://doi.org/10.2305/IUCN.UK.2018-2.RLTS.T14053A100466656.en

Evers DC, Graham RT, Perkins CR, Michener R, Divoll T (2009) Mercury concentrations in the goliath grouper of Belize: an anthropogenic stressor of concern. Endanger Species Res 7(3):249–256. https://doi.org/10.3354/esr00158

FAO. Food and Agriculture Organization (2017) The State of Food Security and Nutrition in the world. In cooperation with IFAD (International Fund for Agricultural Development, UNICEF (United Nations Children´s Fund), WFP (World Food Programme) and WHO (World Health Organization). Building resilience for peace and food security, Rome.

FAO/WHO (2001) Human vitamin and mineral requirements. Report of a joint FAO/WHO expert consultation. Bangkok, Thailand. https://www.fao.org/3/y2809e/y2809e00.pdf

Franco-Fuentes E, Moity N, Ramírez-González J, Andrade-Vera S, Hardisson A, Paz G-W, S, Rubio C, Gutiérrez ÁJ, (2021) Metals in commercial fish in the Galapagos Marine Reserve: contribution to food security and toxic risk assessment. J Environ Manage 286:112188. https://doi.org/10.1016/j.jenvman.2021.112188

Frías-Espericueta MG, Quintero-Alvarez JM, Osuna-López JI, Sanchez-Gaxiola CM, López-López G, Izaguirre-Fierro G, Voltolina D (2010) Metal contents of four commercial fish species of NW Mexico. Bull Environ Contam Tox 85(3):334–338. https://doi.org/10.1007/s00128-010-0092-z

Froese R, Pauly D (2021) FishBase. World Wide Web electronic publication. https://www.fishbase.org (02/2021). Accessed 20 April 2021

García-Hernández J, Cadena-Cárdenas L, Betancourt-Lozano M, García-De la Parra LM, García-Rico L, Márquez-Farías F (2007) Total mercury content found in edible tissues of top predator fish from the Gulf of California. Mexico Toxicol Environ Chem 89(3):507–522. https://doi.org/10.1080/02772240601165594

Gu YG, Lin Q, Hong-Hui H, Liang-Gen W, Jia-Jia N, Fei-Yan D (2017) Heavy metals in fish tissues/stomach contents in four marine wild commercially valuable fish species from the western continental shelf of South China Sea. Mar Pollut Bull 114:1125–1129. https://doi.org/10.1016/j.marpolbul.2016.10.040

Heba H, Abuzinadah O, Al-Hamadi M, Al-Nedhary A, Zeid IA, Saini K, Farajalla A, Ahmed MM (2014) Detection of heavy metals contamination in greasy grouper (Epinephelus tauvina) and striped mackerel (Rastrelliger kanagurta) from Al Hodeidah, Red Sea coast of Yemen. J Food Agric Environ 12(2):845–850

Hemmadi V (2016) Metallothionein - a potential biomarker to assess the metal contamination in marine fishes - a review. Int J Bioassays 5(4):4961–4973

Huerta-Díaz MA, Muñoz-Barbosa A, Otero XL, Valdivieso-Ojeda J, Amaro-Franco EC (2014) High variability in geochemical partitioning of iron, manganese and harmful trace metals in sediments of the mining port of Santa Rosalia, Baja California Sur, Mexico. J Geochem Explor 145:51–63. https://doi.org/10.1016/j.gexplo.2014.05.014

INEGI (2015) Instituto nacional de estadística y geografía. https://www.beta.inegi.org.mx/areasgeograficas/?ag=03#.

Jezierska B, Lugowska K, Witeska M (2009) The effects of heavy metals on embryonic development of fish (a review). Fish Physiol Biochem 35(4):625–640. https://doi.org/10.1007/s10695-008-9284-4

Jonathan MP, Shumilin E, Rodríguez-Figueroa GM, Rodriguez-Espinosa PF, Sujitha SB (2016) Potential toxicity of chemical elements in beach sediments near Santa Rosalia copper mine, Baja California Peninsula, Mexico. Estuar Coast Shelf Sci 180:91–96. https://doi.org/10.1016/j.ecss.2016.06.015

Leung HM, Leung AOW, Wang HS, Ma KK, Liang Y, Ho KC, Cheung KC, Tohidi F, Yung KKL (2014) Assessment of heavy metals/metalloid (As, Pb, Cd, Ni, Zn, Cr, Cu, Mn) concentrations in edible fish species tissue in the Pearl River delta (PRD). China Mar Poll Bull 78(1–2):235–245. https://doi.org/10.1016/j.marpolbul.2013.10.028

Lozano G, Brito A, Hardisson A, Gutiérrez Á, González-Weller D, Lozano IJ (2009) Content of lead and cadmium in barred hogfish, Bodianus scrofa, island grouper, Mycteroperca fusca, and Portuguese dogfish, Centroscymnus coelolepis, from Canary Islands. Spain Bull Environ Contam Toxicol 83(4):591–594. https://doi.org/10.1007/s00128-009-9809-2

Madany IM, Wahab AAA, Al-Alawi Z (1996) Trace metals concentrations in marine organisms from the coastal areas of Bahrain, Arabian Gulf. Water, Air, & Soil Pollut 91(3–4):233–248. https://doi.org/10.1007/bf00666260

Mok WJ, Senoo S, Itoh T, Tsukamasa Y, Kawasaki KI, Ando M (2012) Assessment of concentrations of toxic elements in aquaculture food products in Malaysia. Food Chem 133(4):1326–1332. https://doi.org/10.1016/j.foodchem.2012.02.011

Moreno-Sánchez XG, Pérez-Rojo MP, Irigoyen-Arredondo MS, Marín-Enríquez E, Abitia-Cárdenas LA, Escobar-Sánchez O (2019) Feeding habits of the leopard grouper Mycteroperca rosacea (Streets, 1877) in the central Gulf of California, BCS. México Act Icth Pisc 49(1):9–22. https://doi.org/10.3750/AIEP/02321

Murillo-Cisneros DA, O'Hara TM, Castellini JM, Sánchez-González A, Elorriaga-Verplancken FR, Marmolejo-Rodríguez AJ, Marín-Enríquez E, Galván-Magaña F (2018) Mercury concentrations in three ray species from the Pacific coast of Baja California Sur, Mexico: variations by tissue type, sex and length. Mar Pollut Bull 126:77–85. https://doi.org/10.1016/j.marpolbul.2017.10.060

Nik-Nurasyikin NMA, Nurulnadia MY, Sofi AHM, Jaafar SN (2018) Metals accumulation in cultured tiger grouper, *Epinephelus Fuscoguttatus* with estimated weekly in take levels from east coast of peninsular Malaysia. J Sustain Sci Manag 13(5).

Nikolsky GV (1963) The Ecology of Fishes. Academic Press, New York

NOM-242-SSA1–2009. Norma Oficial Mexicana (2009) Bienes y Servicios. Productos de la pesca. Pescados frescos-refrigerados y congelados. Especificaciones sanitarias. Publicación: 10 de febrero del 2011.

Pal J, Shukla BN, Maurya AK, Verma HO, Pandey G, Amitha A (2018) A review on role of fish in human nutrition with special emphasis to essential fatty acid. Int J Fish Aquat Stud 6(2):427–430

Pérez-Olivas A, Irigoyen-Arredondo MS, Moreno-Sánchez XG, Villalejo-Fuerte MT, Abitia-Cárdenas LA, Escobar-Sánchez O (2018) Reproductive biology of the leopard grouper Mycteroperca rosacea (Streets, 1877) in the coastal area of Santa Rosalía, BCS. Mexico Lat Am J Aquat Res 46(4):699–708. https://doi.org/10.3856/vol46-issue4-fulltext-7

Rajeshkumar S, Li X (2018) Bioaccumulation of heavy metals in fish species from the Meiliang Bay, Taihu Lake, China. Toxicol Rep 5:288–295. https://doi.org/10.1016/j.toxrep.2018.01.007

R Core Team. 2017. R: a language and environment for statistical computing, Vienna, Austria. URL http://CRAN.R-project.org/

Rehman M, Liu L, Wang Q, Saleem MH, Bashir S, Ullah S, Peng D (2019) Copper environmental toxicology, recent advances, and future outlook: a review. Environ Sci Pollut Res 26(18):18003–18016. https://doi.org/10.1007/s11356-019-05073-6

Rodrigues AM, Antunes P, Paulo L, Pereira ME, Pinto de Andrade L (2018) Metal contaminants in largemouth bass (Micropterus salmoides, Lacépéde, 1802) from different origins. Int J Res Agr for 1(5):8–14

Roméo M, Siau Y, Sidoumou Z, Gnassia-Barelli M (1999) Heavy metal distribution in different fish species from the Mauritania coast. Sci Total Environ 232(3):169–175. https://doi.org/10.1016/S0048-9697(99)00099-6

Ruelas-Inzunza JR, Escobar-Sánchez O, Páez-Osuna F (2014) Mercury in fish, crustaceans and mollusks from estuarine areas in the Pacific Ocean and Gulf of Mexico under varying human impact. In: Amezcua F, Bellgraph B (eds) Fisheries management of Mexican and Central American Estuaries. Springer, Netherlands, pp 39–49

Ruelas-Inzunza J, Páez-Osuna F, García-Flores YD (2010) Essential (Cu) and nonessential (Cd and Pb) metals in ichthyofauna from the coasts of Sinaloa state (SE Gulf of California). Environ Monit Assess 162(1–4):251–263. https://doi.org/10.1007/s10661-009-0793-0

Shumilin E, Jiménez-Illescas AF, López-López S (2013) Anthropogenic contamination of metals in sediments of the Santa Rosalía Harbor, Baja California Peninsula. Bull Environ Contam Toxicol 90:333–337. https://doi.org/10.1007/s00128-012-0923-1

Sidoumou Z, Gnassia-Barelli M, Siau Y, Morton V, Roméo M (2005) Distribution and concentration of trace metals in tissues of different fish species from the Atlantic Coast of Western Africa. Bull Environ Contam Toxicol 74(5):988–995. https://doi.org/10.1007/s00128-005-0677-0

Soto-Jiménez MF, Páez-Osuna F, Scelfo G, Hibdon S, Franks R, Aggarawl J, Flegal AR (2008) Lead pollution in subtropical ecosystems on the SE Gulf of California Coast: a study of concentrations and isotopic composition. Mar Environ Res 66(4):451–458. https://doi.org/10.1016/j.marenvres.2008.07.009

Streets TH (1877) Contributions to the natural history of the Hawaian and Fanning Islands and Lower California: made in connection with the United States North Pacific surveying expedition, 1873–75 (No. 7). US Government Printing Office.

Sujitha SB, Jonathan MP, Aurioles-Gamboa D, Villegas LEC, Bohórquez-Herrera J, Hernández-Camacho CJ (2019) Trace elements in marine organisms of Magdalena Bay, Pacific Coast of Mexico: bioaccumulation in a pristine environment. Environ Geochem Health 41(3):1075–1089. https://doi.org/10.1007/s10653-018-0198-5

Tepe Y (2009) Metal concentrations in eight fish species from Aegean and Mediterranean Seas. Environ Monit Assess 159(1):501–509. https://doi.org/10.1007/s10661-008-0646-2

Thomson DA, Findley LT, Kerstitch AN (2000) Reef fishes of the Sea of Cortez: the rocky-shore fishes of the Gulf of California. University of Texas Press, USA

Tremain DM, Adams DH (2012) Mercury in groupers and sea basses from the Gulf of Mexico: relationships with size, age, and feeding ecology. T Am Fish Soc 141(5):1274–1286. https://doi.org/10.1080/00028487.2012.683232

UK EEA (European Environment Agency) (2011) European Union emission inventory report under the UNECE Convention on Long-range Transboundary Air Pollution (LRTAP). Technical Report No 9/2011. Copenhagen.

US EPA. United States Environmental Protection Agency (2015) Risk-based screening table. https://www.epa.gov/risk/regional-screening-levels-rsls-generic-tables. Accessed 25 May 2020

Vincent-Akpu IF, Yanadi LO (2014) Levels of lead, iron and cadmium contamination in fish, water and sediment from Iwofe site on New Calabar River. Rivers State Int J Extensive Res 3:10–15

Xia W, Chen L, Deng X, Liang G, Giesy JP, Rao Q, Wen Z, Wu Y, Chen J, Xie P (2019) Spatial and interspecies differences in concentrations of eight trace elements in wild freshwater fishes at different trophic levels from middle and eastern China. Sci Total Environ 672:883–892. https://doi.org/10.1016/j.scitotenv.2019.03.134

Xu DM, Yan B, Chen T, Lei C, Lin HZ, Xiao XM (2017) Contaminant characteristics and environmental risk assessment of heavy metals in the paddy soils from lead (Pb)-zinc (Zn) mining areas in Guangdong Province. South China Environ Sci Pollut Res 24(31):24387–24399. https://doi.org/10.1007/s11356-017-0052-9

Yi YJ, Zhang SH (2012) The relationships between fish heavy metal concentrations and fish size in the upper and middle reach of Yangtze River. Procedia Environ Sci 13:1699–1707. https://doi.org/10.1016/j.proenv.2012.01.163

Yi YJ, Yang ZF, Zhang SH (2011) Ecological risk assessment of heavy metals in sediment and human health risk assessment of heavy metals in fishes in the middle and lower reaches of the Yangtze River basin. Environ Pollut 159:2575–2585. https://doi.org/10.1016/j.envpol.2011.06.011

Zhang L, Zhu L, Li F, Liu C, Yang Z, Qiu Z, Xiao M (2017) Heavy metals and metalloid distribution in different organs and health risk assessment for edible tissues of fish captured from Honghu Lake. Oncotarget 8(60):101672–101685. https://doi.org/10.18632/oncotarget.21901