Chemosphere 267 (2021) 129233

Contents lists available at ScienceDirect

Chemosphere

journal homepage: www.elsevier.com/locate/chemosphere

Mercury concentrations in Baja California Sur fish: Dietary exposure assessment

Daniela A. Murillo-Cisneros [a], Tania Zenteno-Savín [a, *], John Harley [b], Andrew Cyr [c], Pablo Hernández-Almaraz [a], Ramón Gaxiola-Robles [a, d], Felipe Galván-Magaña [e], Todd M. O'Hara [f]

[a] *Centro de Investigaciones Biológicas Del Noroeste, S.C. Planeación Ambiental y Conservación. Instituto Politécnico Nacional 195, Playa Palo de Santa Rita Sur, La Paz, Baja California Sur, C.P. 23096, Mexico*
[b] *Alaska Coastal Rainforest Center, University of Alaska Southeast, 11175 Auke Lake Way, Juneau, AK, 99801, USA*
[c] *Biomedical Learning and Student Training, University of Alaska Fairbanks, 2141 Koyukuk Dr., Fairbanks, AK, 99775, USA*
[d] *Hospital General de Zona No.1. Instituto Mexicano Del Seguro Social. 5 de Febrero y Héroes de La Independencia, Centro, La Paz, Baja California Sur, C.P. 23000, Mexico*
[e] *Instituto Politécnico Nacional, Centro Interdisciplinario de Ciencias Marinas, Av. I.P.N. S/n, Colonia Playa Palo de Santa Rita, Apartado Postal 592, La Paz, Baja California Sur, C.P. 23000, Mexico*
[f] *Bilingual Laboratory of Toxicology, Veterinary Integrative Biosciences, College of Veterinary Medicine & Biomedical Sciences, Texas A&M University, College Station, TX, 77843, USA*

HIGHLIGHTS

- Dietary Hg exposure was assessed through fish consumption in a Mexican coastal community.
- Fish muscle [THg] varies by length, weight and trophic ecology in most species.
- In all species[THg] was below the threshold set for predatory fish in Mexico.
- The hazard quotients (HQs) in most species were significantly <1.
- The relative level of risk of Hg toxicity is low for most fish species.

ARTICLE INFO

Article history:
Received 15 October 2020
Received in revised form
25 November 2020
Accepted 3 December 2020
Available online 7 December 2020

Handling Editor: Jianying Hu

Keywords:
Baja California Sur
Fish
Elasmobranchs
Hazard quotient
Mercury

ABSTRACT

Total mercury concentrations ([THg]) in muscle were determined in commercial finfish and elasmobranchs from Baja California Sur (BCS), Mexico to evaluate dietary Hg exposure for BCS communities, including the relationship of trophic ecology, length and mass with [THg] that might drive future consumption advice (e.g., recommend limited consumption of large fish for some species). The [THg] ranged from 0.06 to 528.02 μg kg^{-1} ww in finfish and 17.68–848.26 μg kg^{-1} ww in elasmobranchs. Relative to the consumption threshold set for predatory fish in Mexico, all species had a concentration below 1000 μg kg^{-1} ww. As expected, 16 (4.02%) and 75 (18.84%) individual fish were above advisory thresholds of 500 and 200 μg kg^{-1} ww, respectively. The hazard quotients (HQs) in most species were significantly <1.0, only banded guitarfish showed a significant median HQ > 1.0. Thus, the relative level of risk of high Hg exposure is low for most species.

1. Introduction

Seafood is an important cultural and economic marine resource that provides food security and livelihoods to coastal communities around the world (Pellowe and Leslie, 2017; Vianna et al., 2020). In particular, fish are an important source of high-quality protein; rich

---

* Corresponding author.
E-mail addresses: tzenteno04@cibnor.mx, tzentenos@hotmail.com (T. Zenteno-Savín).

https://doi.org/10.1016/j.chemosphere.2020.129233
0045-6535/

in nutrients such as omega-3 polyunsaturated fatty acids, vitamins and minerals (Olmedo et al., 2013; Gribble et al., 2015; Matos et al., 2015). A large number of studies have documented the health benefits of regular fish consumption, such as reducing risk of coronary heart disease and improved neurodevelopment (Domingo et al., 2007; Gribble et al., 2015).

In contrast to the health benefits of consumption, fish contain contaminants that may have adverse effects on human health, such as mercury (Hg), especially as monomethyl mercury ($MeHg^+$; Matos et al., 2015). $MeHg^+$ is a neurotoxic environmental contaminant of concern due to its high bioavailability and capacity to accumulate and magnify through marine food webs (Harley et al., 2015). Fish are a major pathway for $MeHg^+$ exposure to humans and wildlife, and $MeHg^+$ comprises 80% or more of the total mercury concentrations ([THg]) in fish muscle (Harley et al., 2015). After ingestion, $MeHg^+$ is efficiently absorbed by the gastrointestinal tract (approximately 95%; Clarkson and Magos, 2006a,b), and distributed via the bloodstream to organs and tissues such as muscle. $MeHg^+$ crosses the blood-brain and placental barriers (Hosseini et al., 2013; Kuras et al., 2018), making the developing brain of the fetus a key target organ. At certain exposure levels, $MeHg^+$ can disrupt the endocrine system and negatively affect reproduction, as well as disrupt a range of neurological processes and the immune system (Mergler et al., 2007; Dietz et al., 2013). Thus, in order to minimize health risks, many government agencies set advisory levels to limit the amount of $MeHg^+$ ingested using suggested consumption rates of fish, usually by species, relative to THg or $MeHg^+$ concentrations in muscle. The Mexican government set a limit of 1000 $\mu g\ kg^{-1}$ of THg wet weight (ww) for predatory fish such as tuna, marlin and sharks, and 500 $\mu g\ kg^{-1}$ THg ww for most retail fish (NOM 242-SSA1, 2009). However, these limits do not provide dietary advice (e.g., consumption rates, portion size) or consider key biological factors within a species (e.g., size) to reduce $MeHg^+$ exposure (targeted advice), which makes it crucial to carry out characterization of individual fish Hg to better protect human health from $MeHg^+$ toxicosis while maintaining use of a key source of nutrition.

Baja California Sur (BCS) is a state of Mexico nearly surrounded by ocean (Gulf of California and Pacific Ocean) where marine resources use is of primary economic and cultural importance, and fish constitute a food of easy access for local communities (Ojeda-Ruiz et al., 2018). However, most studies about contaminant exposure via consumption of fish in BCS have focused on top predators such as sharks, rays, tuna and marlin (Escobar-Sánchez et al., 2010, 2011; Maz-Courrau et al., 2012; Barrera-García et al., 2012) with limited published studies on important commercial finfish from the region (Harley et al., 2019). Most Mexican exposure to mercury from fish consumption risk assessments involve commercially important fish from Sonora and Sinaloa (García-Hernandez et al. 2007, 2018; Ruelas-Inzuna et al. 2008, 2011, 2012; Zamora-Arellano et al., 2017). No fish consumption guidelines for fish species that may exceed the maximum limit of [THg] have been issued for BCS communities. It is equally important to identify fish with no or limited concern related to Hg. Monitoring [THg] in edible fish portions consumed in BCS is necessary to provide a reliable estimate of exposure of humans to Hg.

Studies (Gaxiola-Robles et al., 2014) have found elevated hair [THg] of pregnant women of BCS, with concentrations in 72% (54/75) of the women above the United States Environmental Protection Agency (USEPA) advisory guideline of 1 $\mu g\ g^{-1}$, and 8% (6/75) exceeding 5 $\mu g\ g^{-1}$ (Hamade, 2014). Frequency of fish consumption contributed significantly to explaining hair [THg] (Gaxiola-Robles et al., 2014) as well as nitrogen (N) stable isotopes as a marker of trophic level (Bentzen et al., 2014). A study of 70 pregnant women from BCS, found lower [THg] in hair (Harley et al., 2019) than the previous studies (Gaxiola-Robles et al., 2014; Bentzen et al., 2014). Nevertheless, Harley et al. (2019) reinforced fish consumption is driving the observed [THg] in humans by studying a broader range of food items and employing Bayesian mixing models. In this context, the aims of the present study are 1) to further characterize [THg] in various species of fish from BCS, 2) to address feeding ecology, body size and mass as major drivers for [THg] in BCS fish relative to human consumption guidance, and 3) to quantitatively evaluate the potential risk that dietary Hg exposure may pose to BCS communities.

2. Material and methods

2.1. Sample collection

Finfish were collected from two different locations from BCS coasts, Punta Lobos located on the Pacific coast, and La Paz located in the Gulf of California. Elasmobranchs were collected from Bahía Tortugas located on the Pacific coast of BCS (Fig. 1). Specimens from Punta Lobos were obtained from local fishermen in 2019, while specimens from La Paz were purchased from fish markets (generally as whole eviscerated fish), between March 2013 and May 2015, according to what was available from fishermen (based on their catch) and on the market for finfish. Elasmobranchs from Bahía Tortugas were captured by local fishermen in 2014, the main three ray species within the artisanal elasmobranchs fisheries of the Pacific coast of BCS were selected (Ramirez-Amaro et al., 2013). In Punta Lobos, fork length and mass were recorded, and approximately 5 g of muscle were obtained with the skin removed and placed in Whirlpaks®. All samples were frozen and transported to the University of Alaska Fairbanks (UAF) and stored frozen (−20 °C). Finfish from La Paz were transported frozen to UAF as purchased in the market, then stored at −20 °C until processing. After thawing at UAF, fork length and mass were recorded, except for eviscerated fish in which total mass was not recorded, and approximately 5 g of muscle tissue were collected. In Bahía Tortugas, size (total length for the Brown smoothhound *Mustelus henlei*, shovelnose guitarfish *Pseudobatos productus* and banded guitarfish *Zapteryx exasperata*, and disc width for the bat ray *Myliobatis californica*) were recorded for each individual fish. Sexual differentiation was determined by the presence of claspers in males. For each specimen, between 5 and 30 g of muscle (dorsal side near the head) was collected. All samples were kept on ice and transported to the laboratory at Centro Interdisciplinario de Ciencias Marinas from Instituto Politécnico Nacional (CICIMAR-IPN, La Paz, BCS, Mexico) and stored frozen (−20 °C). In the laboratory, all tissues were sub-sampled (range 2–20 g each) using a clean stainless-steel scalpel. Samples were then freeze-dried (Labcono, FreeZone 2.5 L) for 24–48 h and homogenized using a porcelain mortar and pestle cleaned between samples with HCl acid at 10% and distilled water. Mass of each sample before and after freeze-drying was determined to calculate percent water in each tissue once a consistent mass was achieved (fully dried), then transported dry to the UAF for [THg] analysis.

2.2. Total mercury concentration ([THg]) analysis

Dried samples received at UAF were analyzed without further processing. Punta Lobos and La Paz fish muscle samples were freeze-dried (Labcono, FreeZone 6 L, Kansas City, Missouri, USA) for 48 h and homogenized using a steel-ball Cryomill (Retsch Inc, Newton, Pennsylvania, USA) for 2 min at 25 Hz. Mass of each sample before and after freeze-drying was recorded to calculate percent moisture. THg analyses for La Paz fish and elasmobranchs were conducted as described by Harley et al. (2019) and Murillo-Cisneros et al. (2018), respectively, and were similar for Punta

Lobos samples. The [THg] was measured using a direct mercury analyzer (DMA-80, Milestone, Shelton, CT, USA; US EPA method 7473) with thermal decomposition, amalgamation and atomic absorption spectrophotometry, in the Wildlife Toxicology Laboratory at UAF, USA. The detection limit was 1 ng. The instrument was calibrated using a 17-point calibration curve ranging from 0.5 to 500 ng THg. Blanks, aqueous standard (100 ng at 1 mg kg^{-1}, PerkinElmer), and standard reference materials (DORM-4, TORT-2 National Research Council Canada, Ottawa ON, Canada; and Lake Superior Fish, LSF, National Institute of Standards and Technology, Standard Reference Material) were used. Percentage recovery of the standard reference materials and aqueous standards were within 90—107%. Each sample was analyzed in duplicate and the coefficient of variation for duplicate samples was <15%.

2.3. Carbon and nitrogen stable isotopes analysis

For stable isotopes analysis, only fish samples from La Paz were analyzed. C and N stable isotope values were determined at the Alaska Stable Isotope Facility at UAF using a continuous-flow isotope ratio mass spectrometry (CF-IRMS, Thermo DeltaVPlus interfaced with a Costech ESC 4010 elemental analyzer using a ConfloIV system) as described by Cyr et al. (2019). Between 0.2 and 0.5 mg of dry muscle was weighed on an analytical microbalance and placed in a tin capsule (3.5 × 5 mm). Stable isotope ratios of the samples and standards are expressed in δ notation as parts per thousand (‰) relative to international standards (Vienna PeeDee Belemnite – VPDB for carbon and AIR for nitrogen) and calculated using the following formula:

$$\delta^{15}N \text{ or } \delta^{13}C = \left[\left(R_{sample}/R_{standard}\right) - 1\right] \times 1000\ (\%)$$

where R is the ratio of the heavy to light isotope measured for that element. Reference checks using peptone (No. P-7750 meat-based protein. Sigma Chemical Company) were run every 10th sample and blanks every 20th sample. The analytical error for δ^{15}N and δ^{13}C values were approximately <0.2‰.

2.4. Statistical analyses

Normality and homogeneity of variances were assessed with Kolmogorov-Smirnov and Bartlett tests. A Kruskal-Wallis test was performed to determine differences in [THg] between species. Only species with a sample number ≥5 were included in the statistical analysis. A post-hoc analysis was done using multiple comparisons of mean ranks tests. Spearman rank correlation was performed to evaluate the relationship between the feeding ecology drivers (δ^{13}C and δ^{15}N) and [THg] in finfish species. To examine THg biomagnification throughout the food web, the food web magnification factor (FWMF) within the finfish assemblage was determined using a simple linear regression analysis between δ^{15}N (as indicator for trophic position) and log-transformed [THg]. The FWMF was calculated as antilog of the regression slope with base 10 (Borga et al., 2011). A slope statistically greater than 1.0 suggests significant THg magnification in the food web, whereas a slope significantly lower than 1.0 represents biodilution, suggesting active elimination or interrupted trophic transfer (Dehn et al., 2006). A *t*-test and 95% confidence intervals were used to determine if the FWMF was statistically greater than 1.0. Statistical significance was

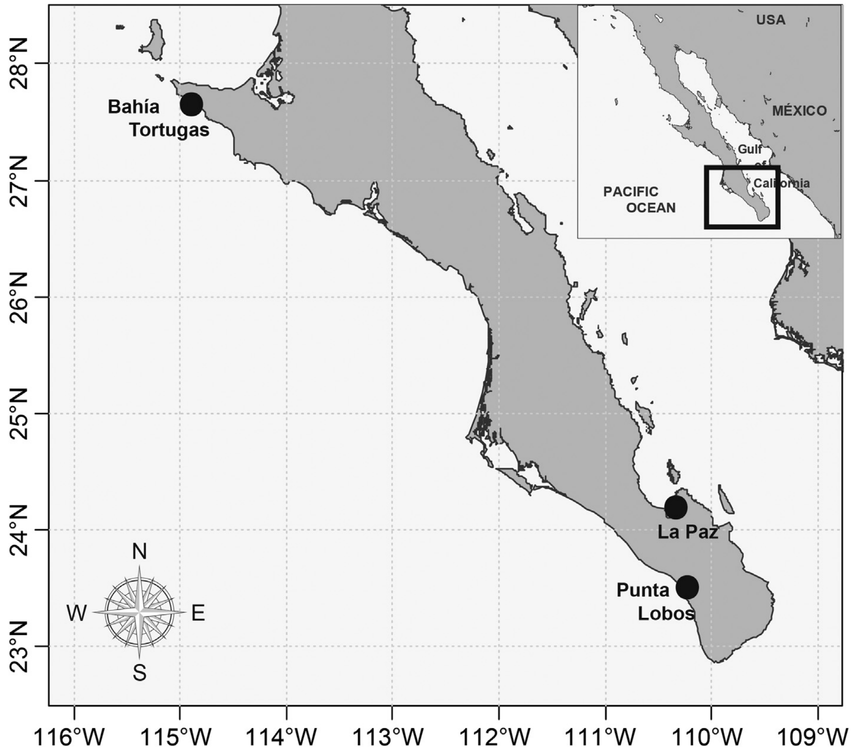

Fig. 1. Location of coastal sites from Baja California Sur where fish and elasmobranchs were collected.

set at $p < 0.05$. All statistical analyses were performed using Statistica 8.0 (statSoft Inc. Tulsa, OK, USA). Sigma plot 12.0 (Systat Software, Inc. Chicago, IL, USA) was used to create graphs.

2.5. Intake calculations

Estimated weekly intake (EWI) of THg was calculated through consumption of each finfish and elasmobranch species, according to the following formula:

$$EWI = \frac{\text{Amount of fish ingested per week } \left(\frac{g}{\text{week}}\right) * \text{Median [THg] in fish}}{\text{Kilogram body mass (kg bw)}}$$

The Mexican population estimated national mean fish consumption per week is 250 g (35.71g per day) and an average adult body mass (bw) of 70 kg for men and 60 kg for women (Ordiano-Flores et al., 2011; CONAPESCA, 2017). The EWI was compared with the reference dose (RfD) recommended by the USEPA in the Integrated Risk Information System in 2001, to generate the hazard quotient (HQ). The RfD is an estimate of a daily exposure of the human population (including sensitive subgroups) to a contaminant in food that can be ingested without any risk to health over a typical life span, 0.0001 mg kg^{-1} day (equivalent to 0.1 μg kg^{-1} day) for $MeHg^{+}$ (US EPA, 2000). The HQ is calculated as the EWI divided by the RfD, where $HQ > 1.0$ represents a potential risk of developing adverse health effects, and an $HQ < 1.0$ means no adverse health effects are expected. One-sample Wilcoxon signed rank test was performed to determine if HQ values were significantly greater, lower or not different from 1.0. Finally, the maximum allowable weekly intake (MWI) of the muscle of each fish species was calculated using the formula (US EPA, 2000):

$$MWI = \frac{RfD * bw}{\text{[THg] in fish}}$$

In Mexico, it is recommended to eat fish two or three times per week (Procuraduría Federal del Consumidor, 2017). Considering a meal serving size of 200 g, those MWI values ≥ 200, <400 g are one serving per week; MWI ≥400, <600 g two servings per week, and MWI ≥600, <800 g three times per week. There were some species with limited sample size and size class. Only species with a sample number ≥5 were included in the statistical analysis.

3. Results

3.1. Total mercury concentrations in Baja California Sur fish

A total of 118 muscle samples from 16 finfish species were analyzed for [THg], 42 belonging to 7 species from La Paz, and 76 belonging to 14 species from Punta Lobos. For elasmobranchs, 280 muscle samples were analyzed, belonging to four species from Bahía Tortugas (one shark and three rays; Table 1). The [THg] showed a wide range of values, from 13.05 to 462.10 μg kg^{-1} ww in finfish from La Paz, and from 0.06 to 528.02 μg kg^{-1} ww in finfish from Punta Lobos, while elasmobranchs [THg] ranged from 17.68 to 848.26 μg kg^{-1} ww. No significant differences were detected in [THg] for any of the finfish species analyzed between both localities ($U = 1527.00$, $p = 0.70$), thus samples from separate locations were pooled for each species for further analysis.

Significant differences in median [THg] between finfish (bony) species were found, with significantly higher concentrations in Peruvian mojarra (*Diapterus peruvianus*) and green jack (*Caranx caballus*) than finescale triggerfish (*Balistes polylepis*), threadfin bass (*Pronotogrammus multifasciatus*) and red snapper (*Lutjanus peru*), as well as significantly higher concentrations in ocean whitefish (*Caulolatilus princeps*) than threadfin bass ($H = 50.77$, $p < 0.001$; Table 1). Elasmobranchs showed significant differences in the median [THg] between species, higher [THg] for banded guitarfish > shovelnose guitarfish > bat ray ($p < 0.05$); no significant differences were found with brown smoothhound ($p > 0.05$).

Most finfish species had limited mass and size class representation that precluded properly exploring the relationship of size and mass with [THg] therefore, only species with a sample size >10 were used for this analysis. According to Spearman rank correlation [THg] increased with 1) fork length ($rs = 0.70$, $p < 0.001$) and mass ($rs = 0.54$, $p = 0.04$) for ocean whitefish (*Caulolatilus princeps*), 2) fork length ($rs = 0.86$, $p < 0.001$) and mass ($rs = 0.91$, $p < 0.001$) for rose snapper (*Lutjanus guttatus*), and 3) mass ($rs = 0.51$, 0.04) but not fork length ($rs = 0.43$, $p = 0.06$) for finescale triggerfish (Fig. 2). There was no increase in [THg] with fork length and mass in Peruvian mojarra, red snapper or threadfin bass, likely because of the sample size and limited size class represented. [THg] increased with total length in brown smoothhound shark ($rs = 0.69$, $p = 0.009$, Fig. 2).

Due to the relatively low sample size (≤6) for each species with known stable isotopes values, the finfish species were pooled for a cross species assessment. The [THg] increased with the increasing $\delta^{13}C$ ($rs = 0.56$, $p < 0.001$; Fig. 3). Peruvian mojarra was an atypical case where this species has a low trophic position (low $\delta^{15}N$) and high muscle [THg], as was previously reported (Harley et al., 2019). When removed from the pooled analysis, [THg] increased with trophic position ($\delta^{15}N$) for the remaining species ($rs = 0.65$, $p < 0.001$; Fig. 3). The FWMF was determined to be 1.46 and statistically greater than 1.0 within the finfish assemblage minus Peruvian mojarra. For elasmobranchs, detailed description of the statistical analysis, results and discussion of the influence of body size, sex and feeding ecology on the [THg] in the three ray species of this study are found in Murillo-Cisneros et al. (2018, 2019). These will be reviewed in the Discussion.

3.2. Strategic intake estimates and comparison to thresholds

Relative to the threshold set for predatory fish in Mexico, all species included in this species had a concentration below 1000 μg kg^{-1} ww. One leopard grouper *Mycteroperca rosacea*, 2 (2.4%) bat ray, 2 (2.1%) shovelnose guitarfish, and 11 (12.6%) banded guitarfish had [THg] in muscle above the permissible limit for the majority of retail fish for human consumption (500 μg kg^{-1} ww) in Mexico. Furthermore, 2 (29%) green jack, 3 (14%) ocean whitefish, 3 (16%) finescale triggerfish, 1 (20%) leopard grouper, 5 (42%) Peruvian mojarra, 8 (11%) bat ray, 10 (10%) shovelnose guitarfish, and 39 (45%) banded guitarfish exceeded the unrestricted consumption threshold set by Alaska Scientific Advisory Committee for Fish

Table 1

Total mercury concentrations in Baja California Sur bony fish and elasmobranch muscle ($\mu g\ kg^{-1}$, wet weight).

Species	Common name		n	Locality	50th percentile (median)	75th percentile	Min	Max
	Spanish	English						
Bony fishes								
Balistes polylepis	Cochito	Finescale triggerfish	19	LP, PL	17.69^{b}	90.28	0.06	393.79
Pronotogrammus multifasciatus	Serrano	Threadfin bass	10	PL	24.12^{bd}	36.04	0.15	53.55
Lutjanus peru	Huachinango	Red snapper	10	LP, PL	33.87^{b}	38.59	19.77	63.44
Lutjanus guttatus	Pargo lunarejo	Rose snapper	12	PL	47.60	137.98	2.12	173.34
Scomberomorus sierra	Sierra	Pacific sierra	7	LP, PL	73.71	80.60	65.83	146.46
Caulolatilus princeps	Pierna	Ocean whitefish	21	LP, PL	75.24^{c}	125.17	22.73	363.92
Lutjanus argentiventris	Pargo	Yellow snapper	5	LP	81.71	110.56	42.15	115.87
Halichoeres nicholsi	Vieja	Spinster wrasse	1	PL	85.52			
Mycteroperca rosacea	Cabrilla	Leopard grouper	5	LP, PL	86.65	146.36	66.87	528.02
Sebastes macdonaldi	Rocote Mexicano	Mexican rockfish	2	PL			66.08	97.32
Sufflamen verres	Taxi	Orangeside triggerfish	1	PL	98.43			
Alphestes multiguttatus	Alphestes	Rivulated mutton hamlet	1	PL	128.97			
Caranx caballus	Jurel	Green jack	7	PL	167.10^{a}	223.50	103.90	300.90
Diapterus peruvianus	Mojarra	Peruvian mojarra	12	LP	178.40^{a}	280.90	107.10	462.10
Pristigenys serrula	Cardenal	Popeye catalufa	4	PL	227.8	277.5	107.6	308.5
Scorpaena guttata	Escorpión Californiano	California scorpionfish	1	PL	352.8			
Elasmobranchs								
Myliobatis californica	Tecolote	Bat ray	83	BT	58.04^{C}	82.51	17.68	646.72
Pseudobatos productus	Guitarra blanca	Shovelnose guitarfish	97	BT	82.48^{B}	136.01	37.26	693.79
Mustelus henlei	Tiburón mamón	Brown smoothhound	13	BT	91.89	99.22	55.13	119.73
Zapteryx exasperata	Guitarra bandeada	Banded guitarfish	87	BT	181.25^{A}	333.39	34.17	848.26

n: number of samples, Min: minimum, Max: maximum, LP: La Paz, PL: Punta Lobos, BT: Bahía Tortugas.

Significant differences ($p < 0.05$) are denoted by different letters in finfish species (“a” higher than “b”; “c” higher than “d”) and capital letters in elasmobranchs species (“A” higher than “B” and “C”; “B” higher than “C”).

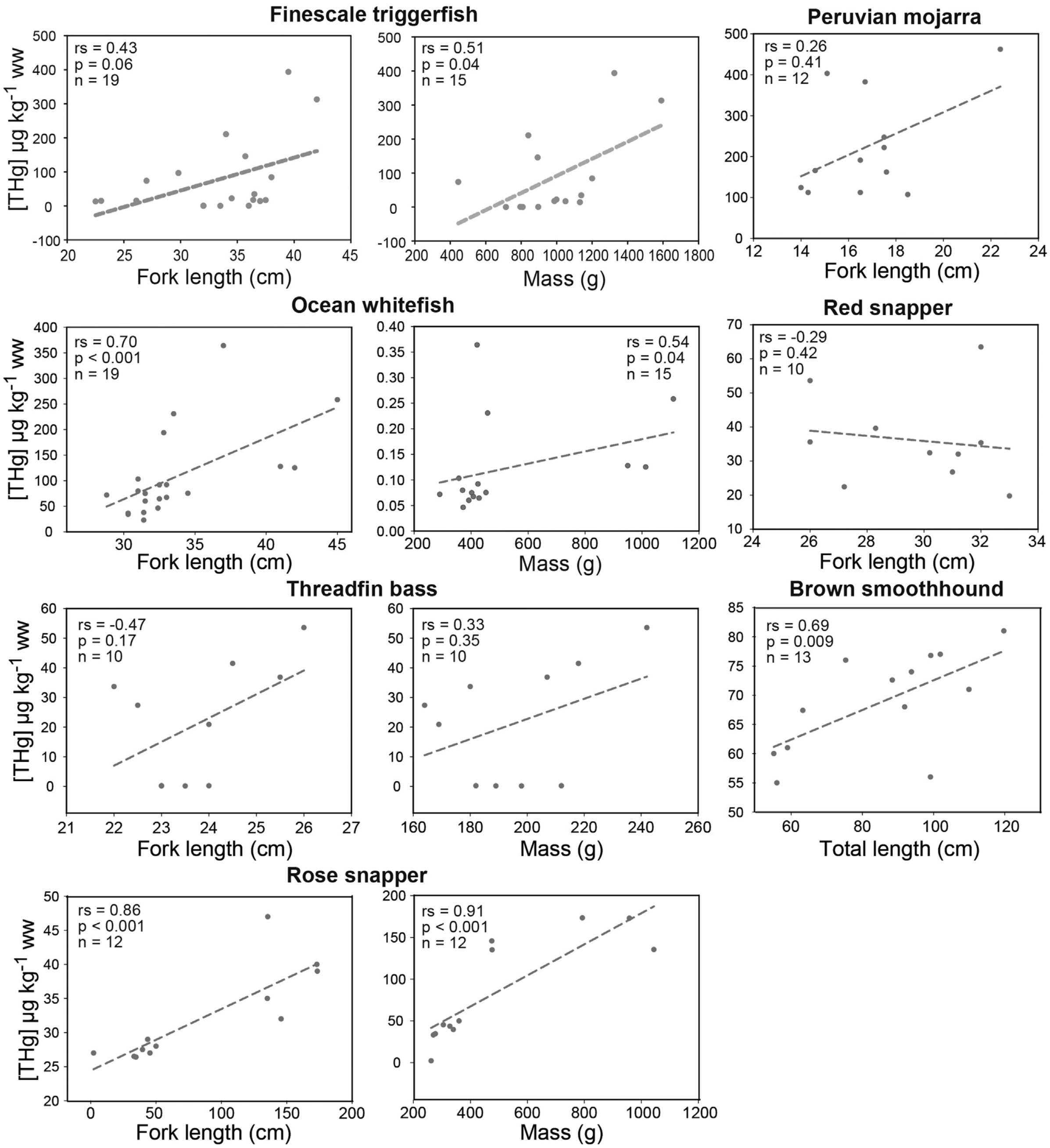

Fig. 2. Relationship between body size and weight with total mercury concentration ([THg]) in finfish species from Baja California Sur.

Consumption of 200 µg kg^{-1} ww (Hamade, 2014). To better address human health risks relative to fish size, [THg] and HQ values are presented by size class for three ray species (Table 2), as the species with a relatively large sample size in this study. Individuals started to exceed [THg] of 200 µg kg^{-1} ww at >60 cm of disc width in the bat ray, > 90 cm in total length in the shovelnose guitarfish and >60 cm in total length in the banded guitarfish (Table 2).

The EWI, MWI and HQ values are presented in Table 3. The banded guitarfish was the only species with a median HQ value significantly greater than 1.0 for women of 60 kg. However, by size class, banded guitarfish showed individuals between >80 and 90 and > 90–103 cm in total length with HQ values significantly greater than 1.0 for men and women of 70 and 60 kg, respectively (Table 2). The amount of fish that a man and woman of 70 and 60 kg, respectively, can consume was highly variable depending on fish species (Table 3). Finescale triggerfish and threadfin bass were the species with the widest range of MWI values. For finescale triggerfish, the lowest MWI values correspond to the heaviest fish with the highest [THg] for this species. However, for threadfin bass there is relatively high variability within organisms of similar mass and body size. Thus, increased sample number and size class representation are necessary to have a clearer understanding of [THg]

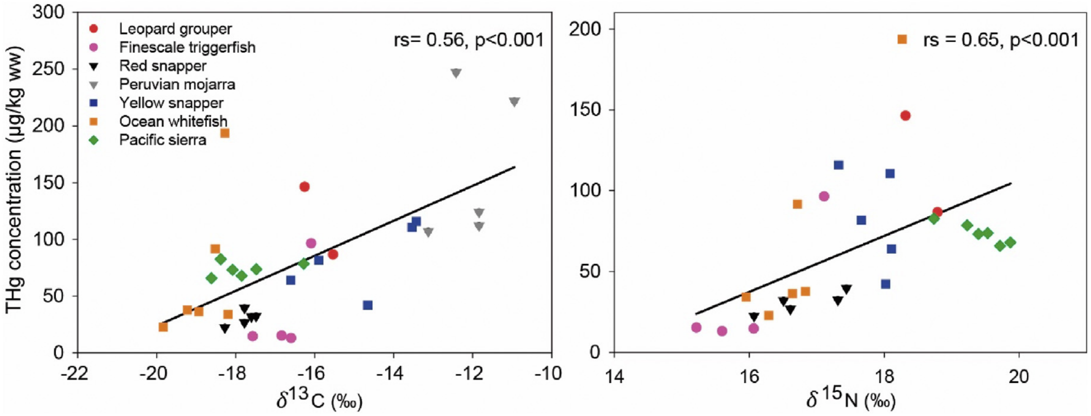

Fig. 3. Relationship between feeding habitat ($\delta^{13}C$) and trophic position ($\delta^{15}N$) with total mercury concentration ([THg]) in finfish species from Baja California Sur.

Table 2

Median muscle total mercury concentration ([THg]) and hazard quotient (HQ) values in three ray species by size class (μg kg^{-1} ww), from Bahía Tortugas, Baja California Sur. Disc width for bat ray and total length for shovelnose guitarfish and banded guitarfish.

Body size (cm)	N	Median [THg]	Range [THg]	% fish containing >200 μg kg^{-1} ww	% fish containing >500 μg kg^{-1} ww	70 kg men Median HQ	60 kg women Median HQ
Bat ray (*M. californica*)							
18–30	18	47.22	19.38–82.25	0	0	0.24	0.28
>30-40	17	43.57	17.68–83.33	0	0	0.22	0.26
>40-50	11	47.99	23.65–70.21	0	0	0.24	0.29
>50-60	10	69.18	21.28–82.77	0	0	0.35	0.41
>60–70	**14**	**71.29**	**43.47–386.75**	14.29	0	0.36	0.42
>70-80	4	172.84	127.07–367.32	50	0	0.88	1.03
>80-90	6	186.08	135.21–646.72	50	3.33	0.95	1.11
>90-100	1	168.16	–	0	0	0.86	1.00
>100-110	1	269.66	–	100	0	1.38	1.61
>110-120	1	392.29	–	100	0	2.00	2.34
Shovelnose guitarfish (*P. productus*)							
49–70	3	104.39	37.26–174.66	0	0	0.53	0.62
>70-80	4	61.89	42.31–66.47	0	0	0.21	0.37
>80-90	15	70.48	43.50–163.79	0	0	0.36	0.42
>90–100	**38**	**77.02**	**47.91–233.17**	10.53	0	0.39	0.46
>100-110	22	109.85	57.33–541.02	13.64	4.55	0.56	0.65
>110-120	9	153.49	96.00–693.79	33.33	11.11	0.78	0.91
>120-130	2	–	149–153.89	0	0	–	–
Banded guitarfish (*Z. exasperata*)							
51–60	7	60.64	35.29–64.29	0	0	0.31	0.36
>60–70	**11**	**64.65**	**34.16–225.72**	9.09	0	0.33	0.39
>70-80	19	119.86	67.75–276.07	21.05	0	0.61	0.71
>80-90	40	236.92	72.39–740.19	62.50	15	1.21*	1.41*
>90-103	10	464.56	140.40–848.26	90	50	2.37*	2.77*

Data from Murillo-Cisneros et al. (2018).

*Denotes HQ values significantly greater than 1.0, potential risk related to monomethyl mercury exposure (using a chronic oral reference dose of 0.1 μg kg^{-1} day).

Bolded indicates first occurrence of [THg] > 200 μg kg^{-1} ww for an individual organism.

for this species to better address human health risks relative to fish size. According to the MWI values found in this study, species such as finescale triggerfish, rose snapper, red snapper and threadfin bass can be consumed three times per week (meal size 200 g) for both men and women of 70 and 60 kg, respectively. Only ocean whitefish, yellow snapper (*Lutjanus argentiventris*) and Pacific sierra (*Scomberomorus sierra*) can be eaten three times per week for men of 70 kg and two times per week for women of 60 kg. Leopard grouper, brown smoothhound, and shovelnose guitarfish can be consumed two times per week for men and women (70 and 60 kg, respectively). Green jack, Peruvian mojarra and banded guitarfish are limited to one time per week for both human adult classes.

4. Discussion

4.1. Mercury concentrations in fish from Baja California Sur

Ecological and biological factors influence bioaccumulation and biomagnification of THg in aquatic organisms, driving variations in concentrations among individuals, populations and species (Trudel and Rasmussen 2006; Dang and Wang, 2012). In this study, most species had lower [THg] than reported in other studies for fish species of the same family (Table 4). Differences in Hg bioavailability due to physical and chemical characteristics of a given ecosystem, food web structure between ecosystems, and point

Table 3
Median and range of estimated weekly intake (EWI), Maximum allowable weekly intake (MWI) and hazard quotient (HQ) for fish species from Baja California Sur, Mexico, for adult men and women.

Species	Adult men (70 kg)			Adult women (60 kg)		
	EWI (μg kg^{-1} bw per week)	MWI (kg per week)	HQ	EWI (μg kg^{-1} bw per week)	MWI (kg per week)	HQ
	Median (Range)	Median (Range)	Median (Range)	Median (Range)	Median (Range)	Median (Range)
Bony fishes						
Finescale triggerfish	0.06 (<0.001–1.41)	2.77 (0.12–794.21)	0.09** (<0.001–2.01)	0.074 (<0.001–1.64)	2.34 (2.34–680.75)	0.11** (<0.001–2.34)
Green jack	0.60 (0.37–1.07)	0.29 (0.16–0.47)	0.85*** (0.53–1.54)	0.70 (0.43–1.25)	0.25 (0.14–0.40)	0.99*** (0.62–1.79)
Ocean whitefish	0.27 (0.08–1.30)	0.65 (0.13–2.16)	0.38** (0.12–1.86)	0.31 (0.09–1.52)	0.56 (0.12–1.85)	0.45** (0.14–2.17)
Peruvian mojarra	0.64 (0.38–1.65)	0.28 (0.11–0.46)	0.91** (0.55–2.36)	0.74 (0.45–1.93)	0.24 (0.09–0.39)	1.06** (0.63–2.75)
Yellow snapper	0.29 (0.15–0.41)	0.60 (0.42–1.16)	0.42** (0.22–0.59)	0.34 (0.18–0.48)	0.51 (0.36–1.00)	0.49** (0.25–0.69)
Rose snapper	0.17 (0.008–0.62)	1.03 (0.28–23.12)	0.24** (0.01–0.88)	0.20 (0.009–0.72)	0.88 (0.24–19.81)	0.28** (0.01–1.03)
Red snapper	0.12 (0.07–0.23)	1.45 (0.77–2.48)	0.17** (0.10–0.32)	0.14 (0.08–0.26)	1.24 (0.66–2.12)	0.20** (0.12–0.38)
Leopard grouper	0.31 (0.24–1.89)	0.57 (0.09–0.73)	0.44*** (0.34–2.69)	0.36 (0.28–2.20)	0.48 (0.08–0.63)	0.52*** (0.40–3.14)
Threadfin bass	0.09 (<0.001–0.19)	2.07 (0.92–330.67)	0.12** (<0.001–0.27)	0.10 (<0.001–0.22)	1.77 (0.78–283.43)	0.14** (<0.001–0.32)
Pacific sierra	0.26 (0.24–0.52)	0.66 (0.33–0.74)	0.38** (0.34–0.74)	0.31 (0.27–0.61)	0.57 (0.29–0.64)	0.44** (0.39–0.87)
Elasmobranchs						
Brown smoothhound	0.33 (0.20–0.43)	0.54 (0.41–0.89)	0.47** (0.28–0.61)	0.38 (0.23–0.50)	0.46 (0.35–0.76)	0.55** (0.33–0.71)
Bat ray	0.21 (0.06–2.31)	0.84 (0.08–2.77)	0.30** (0.09–3.30)	0.24 (0.07–2.69)	0.72 (0.06–2.38)	0.35** (0.11–3.85)
Shovelnose guitarfish	0.29 (0.13–2.48)	0.59 (0.07–1.32)	0.42** (0.19–3.54)	0.34 (0.16–2.89)	0.51 (0.06–1.13)	0.49** (0.22–4.13)
Banded guitarfish	0.65 (0.12–3.03)	0.27 (0.06–1.43)	0.92*** (0.17–4.33)	0.76 (0.14–3.53)	0.23 (0.05–1.23)	1.08* (0.20–5.05)

bw: body mass.
*Denotes HQ values are significantly greater than 1.0, indicating potential risk related to monomethyl mercury exposure (using a chronic oral reference dose of 0.1 μg kg^{-1} day). **Denotes HQ values are significantly less than 1.0. ***Denotes HQ values are significant equal than 1.0.

sources of contaminant inputs may lead to variations in [THg] in marine biota between localities (Lavoie et al., 2013; Wang et al., 2019). Some coastal areas of Sinaloa (southeast Gulf of California) are impacted by anthropogenic activity (agriculture, food processing and aquaculture) that may be related to differences observed in this study (Ruelas-Inzunza et al., 2008, Table 4). Nonetheless, it is likely that differences in fish size classes between studies can explain some observed differences. A study from the Sinaloa coast reported higher [THg] in Peruvian mojarra than this study, which may be related to differences in body size, since organisms from this study are slightly smaller (average 16.77 ± 2.29 cm) than those reported for the southeast Gulf of California (average 21 ± 2 cm; Ruelas-Inzunza et al., 2012). The [THg] in Peruvian mojarra from this study are similar to those reported for Peruvian mojarra of similar body size (average 16.78 ± 1.25 cm) by Spanopoulos-Zarco et al. (2014) on the coast of Guerrero (Eastern Pacific). In addition, the same study (Spanopoulos-Zarco et al., 2014) reported lower [THg] for a species of the same family and smaller body size (average 22.35 ± 1.16 cm) and mass (average 126.48 ± 12.34 g) than green jack from this study (average 36.43 ± 1.88 cm and 745 ± 124.71 g, respectively). García-Hernández et al. (2007) found higher [THg] in leopard grouper of larger body size (73 and 77 cm) than leopard grouper from this study (average 41 ± 3.54 cm). The same authors reported slightly higher [THg] in brown smoothhound shark of similar body size (range: 64–81 cm) than brown smoothhound shark from this study (range: 55–81 cm). Furthermore, for this shark species, we found slightly higher [THg] than reported for the brown smoothhound with a wide range in body size (range: 43.5–102.7 cm) off the Pacific coasts of BCS, Sinaloa and Sonora (Medina-Morales et al., 2020). In addition, variables such as sex, analytical variability, and sample number, could be significant factors in the [THg] variation observed between studies (Karimi et al., 2013; Murillo-Cisneros et al., 2018).

Inter- and intraspecific differences in foraging ecology are reflected in [THg] since the main pathway for the uptake of Hg is diet (Crozier et al., 2016). In general, mainly piscivorous species were found to have significantly higher [THg] than species that feed mostly on invertebrates. Green jack, which feeds on higher trophic level prey (mainly fishes; Saucedo-Lozano et al., 2012), and Peruvian mojarra had the highest [THg]. Finescale triggerfish, threadfin bass and red snapper are carnivorous fish, feeding mainly upon prey of lower trophic positions such as crustaceans and mollusks (Smith-Vaniz et al., 2010; Moreno-Sánchez et al., 2016; Valencia-Valdez, 2017) and had the lowest [THg].

4.2. Size, mass and trophic ecology

Feeding behavior, body size and weight are well-known factors driving [THg] in fish (Karimi et al., 2013; Murillo-Cisneros et al. 2018, 2019; Wang et al., 2019). Body size (including as a proxy for age) is a key variable that generally reflects ecological, physiological, behavioral, and morphological changes in organisms that may affect [THg] (Layman et al., 2005; Murillo-Cisneros et al., 2018). Moreover, the effect of fish length on [THg] is one of the most

Table 4
Mean total mercury concentration ([THg], µg kg^{-1}, wet weight) reported in muscle tissue of different fish species from Mexican Pacific coast. Sample size is in parenthesis.

Family	Species	Common name	Mean [THg]	Location	Author
Finfish					
Serranidae	*Mycteroperca jordani*	Gulf grouper	360.0 (6)	Northern GC	García-Hernández et al. (2007)
	Mycteroperca jordani	Gulf grouper	190.0 (2)	Central GC	García-Hernandéz et al. (2018)
	Mycteroperca rosacea	Leopard grouper	340.0 (2)	Northern GC	García-Hernández et al. (2007)
	Epinephelus analogus	Spotted grouper	270.0 (6)	Northern GC	García-Hernández et al. (2007)
Lutjanidae	*Haplopagrus guentherii*	Barred pargo	460.0 (12)	Central GC	García-Hernandéz et al. (2018)
	Lutjanus colorado	Colorado snapper	117.0 (10)	Sinaloa coast SE GC	Ruelas-Inzunza et al. (2008)
Malacanthidae	*Caulolatilus princeps*	ocean whitefish	125.4 (4)	Sinaloa coast SE GC	Ruelas-Inzunza et al. (2008)
Gerreidae	*Diapterus peruvianus*	Peruvian mojarra	127.6 (6)	Sinaloa coast SE GC	Ruelas-Inzunza et al. (2008)
	Diapterus peruvianus	Peruvian mojarra	562.0 (123)	Sinaloa coast SE GC	Ruelas-Inzunza et al. (2012)
	Diapterus peruvianus	Peruvian mojarra	150.0 (62)	Guerrero coast E Pacific	Spanopoulos-Zarco et al. (2014)
Scombridae	*Scomberomorus sierra*	Pacific sierra	140.8 (1)	Sinaloa coast SE GC	Ruelas-Inzunza et al. (2008)
Carangidae	*Caranx caninus*	Pacific crevalle jack	1000.0	Sinaloa coast SE GC	Ruelas-Inzunza et al. (2011)
	Caranx caninus	Pacific crevalle jack	730.0 (2)	Sinaloa coast SE GC	Ruelas-Inzunza et al. (2008)
	Hemicaranx leucurus	Yellowfin jack	40.0 (10)	Guerrero coast E Pacific	Spanopoulos-Zarco et al. (2014)
	Seriola lalandi	yellowtail jack	110.0 (15)	Central GC	García-Hernandéz et al. (2018)
Elasmobranchs					
Sphyrnidae	*Sphyrna lewini*	scalloped hammerhead	1452.0	Sinaloa coast SE GC	Ruelas-Inzunza et al. (2011)
	Sphyrna lewini	scalloped hammerhead	1080.0 (22)		García-Hernández et al. (2007)
	Sphyrna zygaena	Smooth hammerhead	8250.0 (4)		García-Hernández et al. (2007)
Triakidae	*Mustelus henlei*	Brown smooth	180.0 (6)		García-Hernández et al. (2007)
Dasyatidae	*Dasyatis dipterura*	Diamond stingray	946.0 (24)	Sonora coast Northern GC	Ruelas-Inzunza et al. (2013)
	Urolophus halleri	Haller's round ray	1370.0 (10)	BCS coast SW GC	Ruelas-Inzunza et al. (2013)
	Dasyatis brevis	Whiptail stingray	450.0 (12)	Eastern GC	García-Hernández et al. (2007)
Rhinobatidae	*Pseudobatos productus*	Shovelnose guitarfish	890.0 (2)	BCS coast SW GC	Ruelas-Inzunza et al. (2013)
	Pseudobatos productus	Shovelnose guitarfish	310.0 (13)	Eastern GC	García-Hernández et al. (2007)
	Zapteryx exasperata	Banded guitarfish	898.0 (1)	BCS coast E Pacific	Ruelas-Inzunza et al. (2013)
	Zapteryx exasperata	Banded guitarfish	110.0 (7)	Eastern GC	García-Hernández et al. (2007)
Myliobatidae	*Myliobatis californica*	Bat ray	50.0 (6)	Eastern GC	García-Hernández et al. (2007)

GC: Gulf of California, SE: southeast, SW: southwest, E: eastern.

important relationships to consider in human exposure studies on fish species for consumption (Sackett et al., 2013). In this study, there was an increase in [THg] with fork length and mass in finescale triggerfish and ocean whitefish but not for threadfin bass, Peruvian mojarra or red snapper. Body size and mass have been previously found to have a strong positive relationship with [THg] in different fish species, probably resulting from the longer exposure time of older fish (Cai et al., 2007; Burger and Gochfeld, 2001; Cyr et al., 2019). Fish usually exhibit ontogenetic shifts in diet; as fish increase in body size, trophic level typically increases, leading to higher [THg] (Trudel and Rasmussen, 2006; Sackett et al., 2013). $MeHg^{+}$ is effectively distributed to muscle tissue, where it binds to thiol ligands of amino acids (e.g. cysteine) which act as a long-term sink with a slow depuration rate (Leaner and Mason, 2004; Amlund et al., 2007). Thus, accumulation in muscle over time might be related to the observed increase in [THg] with body size and mass in this study. However, the power of statistical analyses of the threadfin bass, Peruvian mojarra and red snapper were hindered by small sample size and narrow size ranges (Fig. 2). Further studies with a larger sample number are needed to better assess [THg] for these species.

Stable isotopes of C and N were used to assess the importance of trophic structure on [THg]. According to $\delta^{13}C$, which we used to infer foraging location, [THg] increased with fish feeding closer to the coast (Fig. 3). This pattern agrees with other studies where fish feeding inshore have higher [THg] compared to those feeding offshore (Bank et al., 2007; Goutte et al., 2015; Crozier et al., 2019). This pattern could be related to a higher Hg methylation rate in coastal environments with large inputs of organic matter (Jędruch et al., 2019), as well as upwelling, atmospheric deposition and wastewater point sources of Hg (Crozier et al., 2019).

As expected, [THg] increased with $\delta^{15}N$ (as a proxy of trophic level) in fish from this study. This finding is explained by biomagnification processes as fish feed at higher trophic levels, which agrees with other studies that found [THg] is partially explained by $\delta^{15}N$ (Cyr et al., 2019; Crozier et al., 2019; Murillo-Cisneros et al., 2019). This positive relationship was observed by removing Peruvian mojarra from the analysis. The Peruvian mojarra in this study was an unusual case as a species with relatively low trophic position with higher [THg] relative to other species of higher trophic position. Information about the ecology of this species is limited, but stomach content analysis from other studies indicate it is likely a benthic carnivorous or omnivorous species that feeds upon animals, plants and detritus (Chávez-Comparán and Gregory-

Hammann, 1989; Ruelas-Inzunza et al., 2012; Spanopoulos-Zarco et al., 2014). For some species, it has been noted that higher [THg] can occur in muscle over liver, as well as higher concentrations in liver over muscle indicating tissue tropism is an important consideration (Harley et al., 2015; Cruz-Acevedo et al., 2019). Further investigations of their ecological (trophic ecology, life history, etc.) and biological (physiology, metabolism, tissue tropism, etc.) characteristics that influence Hg concentrations in muscle tissue are needed to better understand metal accumulation in Peruvian mojarra.

4.3. Human intake considerations

Monitoring [THg] in fish provides a reliable estimate of exposure and significance in humans (Burger and Gochfeld, 2011). This information will allow BCS communities to make informed decisions in order to minimize risk of THg exposure and maximize health benefits of fish consumption. This study provides a baseline of the potential exposure to Hg for the consumption of many commercial fish in BCS.

In general, most fish from this study were below the limit set by the Mexican government and other countries such as Canada and US for predatory fish and retail fish (1000 and 500 μg kg^{-1} ww, respectively) with the exception of a few bat ray, shovelnose guitarfish and banded guitarfish individuals (Canadian Food Inspection Agency, 1998; US Food and Drug Administration, 2007; NOM 242-SSA1, 2009). Some individuals of green jack, ocean whitefish, finescale triggerfish, Peruvian mojarra, bat ray, shovelnose guitarfish and banded guitarfish exceeded the more conservative advisory threshold (for unrestricted consumption) set by Alaska Scientific Advisory Committee for Fish Consumption of 200 μg kg^{-1} ww (Hamade, 2014). Hence, we propose follow-up studies for those species. In addition, considerable variation in [THg] within some species also requires further investigations with a larger sample size. Harley et al. (2019) using the same finfish samples from La Paz Bay as those included in this study, suggested that despite the low [THg] found for these species, there may be seasonal and spatial variations within a species. In addition, the species mean and/or median concentration may not be the best measure given larger fishes (with higher [THg] than smaller fishes) may be eaten for several consecutive meals, providing a series of high exposures (Burger and Gochfeld, 2011). Thus, fish body size is an important factor to consider in human exposure studies. In this study, some of the larger individuals within a species (e.g. finescale triggerfish) displayed the highest HQ value. Because of the inherent variability in [THg] in many fish species (e.g. finescale triggerfish and threadfin bass) larger sample sizes are needed to assess human exposure to Hg. For the ray species included in this study, [THg] are presented by size class (Table 2), where larger organisms of each species had [THg] above the 200 μg kg^{-1} ww. This highlights the importance of limiting consumption of these species, but not others, at certain body sizes where risk of higher Hg exposure likely increases with size.

The MWI found in this study was variable and species dependent (Table 3). Finescale triggerfish and threadfin bass showed a wide range of MWI values, likely a result of limited sample size and size class representation. Banded guitarfish, Peruvian mojarra and green jack had the highest [THg]; thus, a lower amount of fish to consume compared to other species. The Food and Drug Administration (FDA) and USEPA recommend a serving meal size of 113 g, a total weekly consumption of fish between 225 and 340 g, which corresponds to three servings per week (US EPA, 2017). Whereas the Spanish Agency for Food Safety and Nutrition (AESAN) recommend eating fish three to four times per week. Based on the results from this study, we recommend a meal size of 200 g for an adult; consumption of banded guitarfish, Peruvian mojarra and green jack should be limited to once per week, while other species can be eaten up to three times per week, for a man and woman of 70 and 60 kg, respectively.

Using median HQ in the present study, considering the rate of consumption, [THg] in each fish species, and a reference dose (RfD), the relative level of risk of Hg toxicosis is low from all finfish species. For finfish, Peruvian mojarra had the highest HQ value ($HQ = 1.06$), which was statistically equal to 1.0. Similarly, Ruelas-Inzunza et al. (2011) reported an HQ value below 1.0 in several fish species from the coast of Sinaloa, considering a daily consumption of fish of 25 g (175 g per week) and average adult of 70 kg, where Peruvian mojarra had a considerably lower HQ value (<0.2) than reported in our study. Spanopoulos-Zarco et al. (2014) reported an HQ value for Peruvian mojarra of 0.53 considering a daily consumption of fish of 25 g for an adult of 70 kg, and all the 16 species they analyzed had HQ values < 1.0. It is important to consider that there is higher fish consumption and larger meal sizes in coastal communities compared to inland communities. For example, García-Hernández et al. (2018) found that fish and shellfish consumption by women of coastal communities of Sonora was almost ten times higher (mean: 307 ± 325 g per day) than the national average, as a result of the availability and affordability of fishery products in these communities. In addition, they reported a high mean HQ (6.2 ± 6.8.) where the majority (83%) of women analyzed had HQ > 1.0. This high consumption of seafood products and relatively higher [THg] (than this study) in some seafood products likely explain the relatively high HQ calculated in the study of García Hernández et al. (2018). In a survey from another study in Mazatlán (Sinaloa), the general population was found to consume 207 g per day, and people related to fisheries activities were found to consume 423 g per day; canned tuna, sierra, shrimp, tilapia and smoked marlin being the most consumed products (Zamora-Arellano et al., 2017). These values are almost 6 and 12 times higher than the national consumption per capita considered in this study. They also reported an HQ value < 1.0 for the general population and fishing related population that has low consumption of fish, while the sector (general and fishing related population) that has a higher fish consumption rate was found with HQ values ranging from 1.08 to 10.91. Unfortunately, to the authors' knowledge, there is no information on the fish consumption patterns by BCS communities and we recognize there might be a greater potential risk for fishermen and their families due to higher fish consumption. The only study that investigated consumption of fish by BCS residents surveyed 70 pregnant women from BCS and reported that the large proportion of women surveyed consume ocean whitefish and finescale triggerfish (Harley et al., 2019), which are species of lower trophic position and low [THg]. Nonetheless, there was considerable variability in the [THg] in finescale triggerfish. Further studies should evaluate this species considering a larger sample size and number of size classes.

For elasmobranchs, we found a low risk of Hg toxicosis for the consumption of most species included in this study. Banded guitarfish was the only species with a median HQ value significantly greater than 1.0 in rays >80 cm of total length, for men and women of 70 and 60 kg (Table 2). Ruelas-Inzunza et al. (2013) reported in different ray species from the Gulf of California and Pacific coast of BCS, such as the diamond stingray (*Hypanus dipterura*), Haller's round ray (*Urobatis halleri*), giant electric ray (*Narcine entemedor*) HQ values that were lower than those found in this study (from 0.0007 to 0.03). These differences could be related to the consumption of shark, with a meal size of 0.82 g per day (5.74 g per week), and a RfD of 0.5 μg kg^{-1} of body mass of a person per day, while we used a more conservative RfD recommended by the USEPA (0.1 μg kg^{-1} day) and higher fish consumption. In another study, the scalloped hammerhead shark *Sphyrna lewini* from the coast of Sinaloa had a similar HQ (1.04) to banded guitarfish from this study, considering a consumption rate of fish of 25 g per day (175 g per week), a RfD of 0.5 μg kg^{-1} day and an adult of 70 kg (Ruelas-Inzunza et al., 2011).

5. Conclusion

We evaluated the risk from dietary Hg exposure via consumption of commercial finfish and elasmobranchs from BCS to help fill an apparent data gap. Median [THg] and associated risk of Hg exposure in most fish included in this study were generally low. However, caution must be taken with these results because of relatively low sample sizes and limited size classes for most of the fish species analyzed, as well as lack of information about the identity and amount of fish consumed by BCS communities. For elasmobranchs, caution must be taken for the consumption of the banded guitarfish, since the findings from this study suggest that larger individuals from this species may place humans at risk of higher Hg exposure. This study provides initial valuable insights regarding Hg exposure via consumption of commercially important fish species in BCS and highlights the importance of initiating a monitoring program for THg and $MeHg^+$ in fish along with consumption patterns for the BCS communities, which could provide a better assessment of Hg exposure for humans in this area.

Credit author statement

Daniela A. Murillo-Cisneros: Methodology, Validation, Formal analysis, Investigation, Writing – original draft. Tania Zenteno-Savín: Writing – review & editing, Supervision. John Harley: Resources, Validation. Andrew Cyr: Resources, Validation, Writing – review & editing. Pablo Hernández-Almaraz: Resources, Writing – review & editing. Ramón Gaxiola-Robles: Writing – review & editing. Felipe Galván-Magaña: Resources, Funding acquisition, Writing – review & editing. Todd M. O'Hara: Conceptualization, Resources, Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors thank the fishermen from Bahía Tortugas and Punta Lobos for their help in acquisition of samples. The former Wildlife Toxicology Laboratory at University of Alaska Fairbanks, provided THg analyses as expertly managed by J.M. Castellini. A portion of the research support was provided by the UAF BLaST program Award RL5GM118990 (Cyr and Harley), Alaska INBRE, as well as from a 2017 North Pacific Research Board (NPRB) Graduate Student Research Award and is referenced as publication #675. BLaST is supported by the NIH Common Fund, through the Office of Strategic Coordination, Office of the NIH Director with linked awards: TL4GM118992, RL5GM118990 and UL1GM118991. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health. UAF is an affirmative action/equal employment opportunity employer and educational institution: www.alaska.edu/nondiscrimination. Some travel and logistics support, as well as the 2019 sample collections, were provided by Colorado State University College of Veterinary Medicine and Biomedical Sciences for O'Hara and Cyr. Texas A&M University (College of Veterinary Medicine and Biomedical Sciences, O'Hara) supports the lead author as a recent Postdoctoral researcher at CIBNOR. A portion of the research support was provided by the Consejo Nacional de Ciencia y Tecnología (CONACYT) (SALUD 2010-C01-140272 and SALUD 2015-CO1-261224); the Centro de Investigaciones Biológicas del Noroeste (CIBNOR), S.C. (PC2.0, PC0.10, PC0.5); the Comisión Nacional de Investigación en Salud del Instituto Mexicano del Seguro Social (IMSS) (2016-785-013). FGM thanks to Instituto Politécnico Nacional for fellowships (COFAA, EDI).

References

Amlund, H., Lundebye, A.K., Berntssen, M.H.G., 2007. Accumulation and elimination of methylmercury in Atlantic cod (*Gadus morhua* L.) following dietary exposure. Aquat. Toxicol. 83, 323–330.

Bank, M.S., Chesney, E., Shine, J.P., Maage, A., Senn, D.B., 2007. Mercury bioaccumulation and trophic transfer in sympatric snapper species from the Gulf of Mexico. Ecol. Appl. 1 (7), 2100–2110.

Barrera-García, A., O'Hara, T.M., Galván-Magaña, F., Méndez-Rodríguez, L.C., Castellini, J.M., Zenteno-Savín, T., 2012. Oxidative stress indicators and trace elements in the blue shark (*Prionace glauca*) off the east coast of the Mexican Pacific Ocean. Comp. Biochem. Physiol., C 156, 59–66.

Bentzen, R., Castellini, J.M., Gaxiola-Robles, R., Zenteno-Savín, T., Méndez-Rodríguez, L.C., O'Hara, T., 2014. Relationship between self-reported fish and shellfish consumption, carbon and nitrogen stable isotope values and total mercury concentrations in pregnant women (II) from Baja California Sur, Mexico. Toxicol. Rep. 1, 1115–1122. https://doi.org/10.1016/j.toxrep.2014.09.014.

Borga, K., Kidd, K.A., Muir, D.C.G., Berglund, O., Conder, J.M., Gobas, F.A.P.C., Kucklick, J., Malm, O., DE Powell, 2011. Trophic magnification factors: considerations of ecology, ecosystems, and study design. Integrated Environ. Assess. Manag. 8 (1), 64–84.

Burger, J., Gochfeld, M., 2011. Mercury and selenium levels in 19 species of saltwater fish from New Jersey as a function of species, size, and season. Sci. Total Environ. 409, 1418–1429.

Cai, Y., Rooker, J.R., Gill, G.A., Turner, J.P., 2007. Bioaccumulation of mercury in pelagic fishes from the northern Gulf of Mexico. Can. J. Fish. Aquat. Sci. 64, 458–469.

Chávez-Comparán, J.C., Hammann, M.G., 1989. Diet of the mojarras, *Gerres cinereus* and *Diapterus peruvianus* (pisces: gerreidae) in cuyutlan lagoon, colima, Mexico during summer. Cienc. Mar. 15 (3), 71–80.

Clarkson, T., Magos, L., 2006a. The toxicologyof mercury and its chemical compounds. Crit. Rev. Toxicol. 36 (8), 609–662.

Clarkson, T.W., Magos, L., 2006b. The toxicology of mercury and its chemical compounds. Crit. Rev. Toxicol. 36 (8), 609–662. https://doi.org/10.1080/10408440600845619.

Conapesca, 2017. Anuario estadístico de acuacultura y pesca 2017. Comisión Nacional de Acuacultura y Pesca, p. 293.

Crozier, G.L., Schaal, G., Gallon, R., Fall, M., Grand, F.L., Munaron, J.M., Rouget, M.L., Machu, E., Fl Loc'h, Laë, R., De Morais, L.T., 2016. Trophic ecology influence on metal bioaccumulation in marine fish: inference from stable isotope and fatty acid analyses. Sci. Total Environ. 573, 83–95.

Crozier, G.L., Schaal, G., Point, D., Le Loc'h, F., Machu, E., Fall, M., Munaron, J.M., Boyé, A., Walter, P., Laë, R., De Morais, L.T., 2019. Stable isotope analyses revealed the influence of foraging habitat on mercury accumulation in tropical coastal marine fish. Sci. Total Environ. 650, 2129–2140.

Cruz-Acevedo, E., Betancourt-Lozano, M., Arizmendi-Rodríguez, D.I., Aguirre-Villaseñor, H., Márquez, D Aguilera, Hernández, J García, 2019. Mercury bioaccumulation patterns in deep-sea fishes as indicators of pollution scenarios in the northern Pacific of Mexico. Deep Sea Res. Part I 144, 52–62.

Cyr, A.P., López, J.A., Wooller, M.J., AWhiting, R Gerlach, O'Hara, T.M., 2019. Ecological drivers of mercury concentrations in fish species in subsistence harvests from Kotzebue Sound, Alaska. Environ. Res. 177, 108622.

Dang, F., Wang, W.X., 2012. Why mercury concentration increases with fish size? Biokinetic explanation. Environ. Pollut. 163, 192–198. https://doi.org/10.1016/j.envpol.2011.12.026.

Dehn, L.A., Follmann, E.H., Thomas, D.L., Sheffield, G.G., Rosa, C., Duffy, L.K., O'Hara, T.M., 2006. Trophic relationship in an Arctic food web and implications for trace metal transfer. Sci. Total Environ. 362, 103–123.

Dietz, R., Sonne, C., Basu, N., Braune, B., O'Hara, T.M., Letcher, R.J., Scheuhammer, T., Andersen, M., Andreasen, C., Andriashek, D., Asmund, G., Aubail, A., Baagøe, H., Born, E.W., Chan, H.M., Derocher, A.E., Grandjean, P., Knott, K., Kirkegaard, M., Krey, A., Lunn, N., Messier, F., Obbard, M., Olsen, M.T., Ostertag, S., Peacock, E., Renzoni, A., Rigét, F.F., Ju, Skaare, Stern, G., Stirling, I., Taylor, M., Wiig, O., Wilson, S., Aars, J., 2013. What are the toxicological effects of mercury in Arctic biota? Sci. Total Environ. 443, 775–790.

Domingo, J.L., Bocio, A., Gemma, F., Llobet, J.M., 2007. Benefits and risks of fish consumption Part I. A quantitative analysis of the intake of omega-3 fatty acids and chemical contaminants. Toxicology 230, 219–226.

EPA, 2017. EPA-FDA Advice about Eating Fish and Shellfish | Advisories and Technical Resources for Fish and Shellfish Consumption | US EPA. Accessed: 18

August 2020. https://www.epa.gov/fish-tech/epa-fda-fish-advice-technical-information#main-content.

Escobar-Sánchez, O., Galván-Magaña, F., Rosíles-Martínez, R., 2010. Mercury and Selenium Bioaccumulation in the Smooth Hammerhead Shark, Sphyrna zygaena Linnaeus, from the Mexican Pacific Ocean. Bull. Environ. Contam. Toxicol. 84, 488–491. https://doi.org/10.1007/s00128-010-9966-3.

Escobar-Sánchez, O., Galván-Magaña, F., Rosíles-Martínez, R., 2011. Biomagnification of Mercury and Selenium in Blue Shark Prionace glauca from the Pacific Ocean off Mexico. Biol. Trace Elem. Res. 144, 550–559. https://doi.org/10.1007/s12011-011-9040-y.

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

García-Hernández, J., Mi Ortega-Vélez, A.D., Paniagua, Contreras, Aguilera-Márquez, D., García, G Leyva, Torre, J., 2018. Mercury concentrations in seafood and the associated risk in women with high fish consumption from coastal villages of Sonora, Mexico. Food Chem. Toxicol. 120, 367–377.

Gaxiola-Robles, R., Bentzen, R., Zenteno-Savín, T., Labrada-Martagón, V., Castellini, J.M., Celis, A., O'Hara, T., Méndez-Rodríguez, L.C., 2014. Marine diet and tobacco exposure affects mercury concentrations in pregnant women (I) from Baja California Sur, Mexico. Toxicol Rep 1, 1123–1132.

Goutte, A., Cherel, Y., Churlaud, C., Ponthus, J.P., Massé, G., Bustamante, P., 2015. Trace elements in Antarctic fish species and the influence of foraging habitats and dietary habits on mercury levels. Sci. Total Environ. 538, 743–749.

Gribble, M.O., Karimi, R., Feingold, B.J., Nyland, J.F., O'Hara, T.M., Gladyshev, M.I., Chen, C.Y., 2015. Mercury, selenium and fish oils in marine food webs and implications for human health. J. Mar. Biol. Assoc. U. K. 96 (1), 43–59.

Hamade, A.K., 2014. Fish Consumption Advice for Alaskans: A Risk Management Strategy to Optimize the Public's Health. July 21, Alaska Scientific Advisory Committee for Fish Consumption. Section of Epidemiology. Division of Public Health, Department of Health and Social Services, State of Alaska, p. 78.

Harley, J., Lieske, C., Bhojwani, S., Castellini, J.M., López, J.A., O'Hara, T.M., 2015. Mercury and methylmercury distribution in tissues of sculpins from the Bering Sea. Polar Biol. 30, 1535–1543.

Harley, J., Gaxiola-Robles, R., Zenteno-Savín, T., Méndez-Rodríguez, L.C., Alvarez, AE Bencomo, Thiede, A., O'Hara, T.M., 2019. Using carbon and nitrogen stable isotope modelling to assess dietary mercury exposure for pregnant women in Baja California Sur, Mexico. Chemosphere 234, 702–714.

Hosseini, M., Bagher-Nabavi, S.M., Parsa, Y., 2013. Bioaccumulation of trace mercury in trophic levels of benthic, benthopelagic, pelagic fish species, and sea birds from Arvand River, Iran. Biol. Trace Elem. Res. 156, 175–180.

Jędruch, A., Bełdowska, M., Ziółkowska, M., 2019. The role of benthic macrofauna in the trophic transfer of mercury in a low-diversity temperate coastal ecosystem (Puck Lagoon, southern Baltic Sea). Environ. Monit. Assess. 191, 137.

Karimi, R., Frisk, M., Fisher, N.S., 2013. Contrasting food web factor and body size relationships with Hg and Se concentrations in marine biota. 2013. PloS One 8 (9), e74695.

Kuras, R., Janasik, B., Stanislawska, M., Wasowicz, W., 2018. Revision of the reciprocal action of mercury and selenium. Int. J. Occup. Med. Environ. Health 31, 575–592. https://doi.org/10.13075/ijomeh.1896.01278.

Lavoie, R.A., Jardine, T.S., Chumchal, M.M., Kidd, K.A., Campbell, L.M., 2013. Biomagnification of mercury in aquatic food webs: a worldwide meta-analysis. Environ. Sci. Technol. 47 (23), 13385–13394.

Layman, C.A., Ko, Winemiller, Arrington, D.A., Jepsen, D.B., 2005. Body size and trophic position in a diverse tropical food web. Ecology 86 (9), 2530–2535.

Matos, J., Lourenço, H.M., Brito, P., AL, Maulvault, MArtins, L.L., Afonso, C., 2015. Influence of bioaccessibility of total mercury, methyl-mercury and selenium on the risk/benefit associated to the consumption of raw and cooked blue shark (*Prionace glauca*). Environ. Res. 143, 123–129.

Maz-Courrau, A, López-Vera, C, Galván-Magaña, F, Escobar-Sánchez, O, Rosíles-Martínez, R, Sanjuán-Muñoz, A, 2012. Bioaccumulation and biomagnification of total mercury in four exploited shark species in the Baja California Peninsula, Mexico. Bull Environ Contam Toxicol 88 (2), 129–134. https://doi.org/10.1007/s00128-011-0499-1. Epub 2011 Dec 21. PMID: 22187022.

Medina-Morales, SA, Corro-Espinoza, D, Escobar-Sánchez, O, Delgado-AlvaPrez, CGF, Ruelas-Inzunza, J, Frías Espericueta, MG, Jara-Marini, ME, Páez, Fosuna, 2020. Mercury (Hg) and selenium (Se) content in the shark Mustelus henlei (Triakidae) in the northern Mexican Pacific. Environ. Sci. Pollut. Res. 27, 16774–16783.

Mergler, D., Anderson, H.A., Chan, LH Man, Mahaffey, K.R., Murray, M., Sakamoto, M., Stern, A.H., 2007. Methylmercury exposure and health effects in humans: a worldwide concern. Ambio 36 (1), 3–11.

Moreno-Sánchez, X., Abitia-Cardenas, L.A., Trujillo-Renata, G., Navia, A.F., Ramírez-Pérez, J.S., Shirasago-German, B., 2016. Variation of feeding habits of *Lutjanus peru* (ACTINOPTERYGII: perciformes: LUTJANIDAE) caught in two regions of the Gulf of California, Mexico. Acta Ichthyol. Piscatoria 46 (2), 97–108.

Murillo-Cisneros, D.A., O'Hara, T.M., Castellini, J.M., Sánchez-González, A., Elorriaga-Verplancken, F.R., Marmolejo-Rodríguez, A.J., 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.

Murillo-Cisneros, D.A., Tm O'Hara, F.R., erplancken, Elorriaga V., Curiel-Godoy, P., Sánchez-Gónzalez, A., Marmolejo-Rodríguez, A.J., Marín-Enríquez, E., Galván-Magaña, F., 2019. Trophic assessment and isotopic niche of three sympatric ray species of western Baja California Sur, Mexico. Environ. Biol. Fish. 102, 1519–1531.

NOM 242-SSA1, 2009. Norma Oficial Mexicana. Productos y servicios. Productos de la pesca frescos, refrigerados, congelados y procesados. Especificaciones sanitarias y métodos de prueba.

Ojeda-Ruiz, M.A., Ea Marín-Monroy, Hinojosa, G., Arango, A., Flores-Irigollen, JJ Cta-Nieto, Ra Cavieses-Núñez and O Aburto-Oropeza, 2018. Development of fisheries in Bahía Magdalena-Almejas: the need to explore new policies and management paradigms. Ocean Coast Manag. 161, 1–10.

Olmedo, P., Pla, A., Hernández, A.F., Barbier, F., Ayouni, L., Gil, F., 2013. Determination of toxic elements (mercury, cadmium, lead, tin and arsenic) in fish and shellfish samples. Risk assessment for the consumers. Environ. Int. 59, 63–72.

Pellowe, K.E., Leslie, H.M., 2017. Seasonal variability shapes resilience of small scale fisheries in Baja California Sur, Mexico. PloS One 12 (8), e0182200.

Procuraduría Federal del Consumidor, 2017. Pescados y mariscos. | *Procuraduría Federal del Consumidor* | *Gobierno* | *gob.mx, Gob.mx*. Accessed: 19 August 2020. https://www.gob.mx/profeco/documentos/pescados-y-mariscos?state=published.

Rámirez-Amaro, S.R., Cartamil, D., Galván-Magaña, F., González-Barba, G., Graham, J.B., Carrera-Fernández, M., Escobar-Sánchez, O., Sosa-Nishizaki, O., Rochin-Alamillo, A., 2013. The artisanal elasmobranch fishery of the Pacific coast of Baja California Sur, Mexico, management implications. Sci. Mar. 77 (3), 473–487.

Ruelas-Inzunza, J., Meza-López, G., Páez-Osuna, F., 2008. Mercury in fish that are of dietary importance from the coast of Sinaloa (SE Gulf of California). J. Food Compos. Anal. 21, 211–218.

Ruelas-Inzunza, J., Páez-Osuna, F., Ruiz-Fernández, A.C., Zamora-Arellano, N., 2011. Health risk associated to dietary intake of mercury in selected coastal areas of Mexico. Bull. Environ. Contam. Toxicol. 86, 180–188.

Ruelas-Inzunza, J., Sánchez Osuna, K., Amezcua-Martínez, F., Spanpoulos-Zarco, P., LManzano-Luna, 2012. Mercury levels in selected bycatch fish species from industrial shrimp-trawl fishery in the SE Gulf of California. Mar. Pollut. Bull. 64, 2857–2859.

Ruelas-Inzunza, J., Escobar-Sánchez, O., Patrón Gómez, J., Xg Moreno-Sánchez, Olmeda, A Murillo, Spanopoulos-Hernández, M., Corro-Espinosa, D., 2013. Mercury in muscle and liver of ten ray species from Northwest Mexico. Mar. Pollut. Bull. 77, 434–436.

Sackett, D.K., Cope, W.G., Rice, J.A., Aday, D.D., 2013. The influence of fish length on tissue mercury dynamics: implications for natural resource management and human health Risk. Int. J. Environ. Res. Publ. Health 10, 638–659.

Saucedo-Lozano, M., ernal Ornelas, I.H.B., Espino-Barr, E., García-Boa, A., Solís, EG Cabral, Puente-Gómez, M., 2012. Feeding habits of the green jack (*Caranx caballus* Günther, 1868) on the coast of Manzanillo, Colima, México. Open Mar. Biol. J. 6, 28–37.

Smith-Vaniz, B.R.R., Dominici-Arosemena, A., Molina, H., Salas, E., Guzman-Mora, A.G., 2010. *Pronotogrammus multifasciatus*. The IUCN Red List of Threatened Species 2010: e.T183283A8086554. https://doi.org/10.2305/IUCN.UK.2010-3.RLTS.T183283A8086554.en. Accessed:19 June 2020.

Spanopoulos-Zarco, P., Ruelas-Inzunza, J., M Meza-Montenegro, K., Sánchez, Osuna, Amezcua-Martínez, F., 2014. Health risk assessment from mercury levels in bycatch fish species from the coasts of Guerrero, Mexico (eastern pacific). Bull. Environ. Contam. Toxicol. 93, 334–338.

Trudel, M., Rasmussen, J.B., 2006. Bioenergetics and mercury dynamics in fish: a modelling perpective. Can. J. Fish. Aquat. Sci. 63, 1890–1902.

US, EPA, Guidance for Assessing Chemical Contaminant Data for Use in Fish Advisories, 2000. Risk Assessment and Fish Consumption Limits, third ed., ume 2. Environmental Protection Agency, Washington. US.

Valencia-Valdez, H.A., 2017. Contenido estomacales, isotopos estables y elementos traza en peces de Santa Rosalía, Golfo de California. Master Thesis. Centro de Investigaciones Biológicas del Noroeste. CIBNOR, México.

Vianna, G.M.S., Zeller, D., Pauly, D., 2020. Fihseries and policy implications for human nutrition. Curr Environ Health Rep 7 (3), 161–169.

Wang, Y., Xie, Q., Xu, Q., Xue, J., Zhang, C., Wang, D., 2019. Mercury bioaccumulation in fish in an artificial lake used to carry out cage culture. J. Environ. Sci. 78, 352–359.

Zamora-Arellano, N.Y., Ruelas-Inzunza, J., García-Hernández, J., Ilizaliturri-Hernández, C.A., Betancourt-Lozano, M., 2017. Linking fish consumption patterns and health risk assessment of mercury exposure in a coastal community of NW Mexico. Hum. Ecol. Risk Assess. 23 (6), 1505–1521.