Environmental Pollution
December 2020,Volume 267, Pages 115614 (12p.)
https://doi.org/10.1016/j.envpol.2020.115614
https://archimer.ifremer.fr/doc/00648/76031/

Benefit-risk associated with the consumption of fish bycatch from tropical tuna fisheries

Sardenne Fany [1? *], Bodin Nathalie [2, 3, 4], Médieu Anais [1, 3], Antha Marisa [2], Arrisol Rona [2], Le Grand Fabienne [1], Bideau Antoine [1], Munaron Jean-Marie [1], Le Loc'h François [1], Chassot Emmanuel [2, 3]

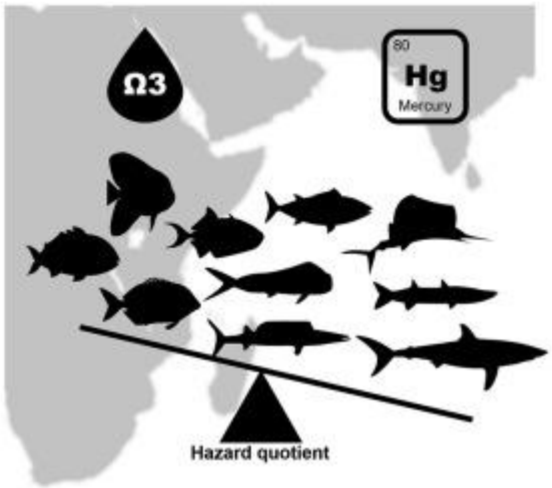
[1] Univ Brest, CNRS, IRD, Ifremer, LEMAR, F-29280 Plouzané, France
[2] Seychelles Fishing Authority (SFA), Fishing Port, Victoria, Mahé, Seychelles
[3] Institute for Research and Sustainable Development (IRD), Fishing Port, Victoria, Mahé, Seychelles
[4] Sustainable Ocean Seychelles (SOS), BeauBelle, Mahé, Seychelles

* Corresponding author : Fany Sardenne

Abstract :

Mercury, omega-3 (docosahexaenoic acid, DHA and eicosapentaenoic acid, EPA) and macronutrients (fat and proteins) were quantified on a wet weight (ww) basis in 20 species of fish taken as bycatch in tropical tuna fisheries. Based on a hazard quotient taking into account mercury and omega-3 contents, a benefit-risk assessment for the consumption of these pelagic species was conducted for three people categories: young children, children and adults. All fish bycatch were found to be an excellent source of proteins (min–max = 14.4–25.2 g/100g fillet), had low omega-6/omega-3 ratios (<1, except for silky shark), and had mercury content below the safety limits defined by sanitary agencies. Silky shark and Istiophoridae had the highest mercury contents (min–max = 0.029–0.317 ppm ww). Omega-3 contents were the lowest in silky shark (0.2±0.2 mg/100g fillet) and the highest in striped marlin (3.6±3.2 g/100g fillet). Billfishes (Istiophoridae, including striped marlin), minor tunas (Scombridae), and Carangidae had the highest omega-3 contents (min–max = 0.68–7.28 g/100g fillet). The highest hazard quotient values obtained for silky shark and great barracuda reflected a lower nutritional benefit (i.e., low omega-3 source) than risk (i.e., mercury exposure), making them not advisable for consumption. Eight species had low hazard quotients, and among them cottonmouth jack and flat needlefish were found of high health interest (high protein, moderate fat contents, and low omega-6/omega-3 ratio). A daily serving portion of 85–200 g (according to people category) can be recommended for these species. Batfish, and to a lower extent pompano dolphinfish and brassy chub, can also be consumed safely and would provide greater health benefits than risks. These results advocate for a better access of these species to local populations.

Graphical abstract



Highlights

► Mercury and omega-3 were quantified in 20 fish species from tuna fisheries bycatch. ► All species are good protein sources, with low omega-6/omega-3 ratio. ► Eight species are of high interest, especially cottonmouth jack and flat needle fish. ► Silky shark and great barracuda are not advised for consumption (low omega-3, high mercury).

Keywords : Contaminant, Polyunsaturated Fatty acids, Hazard quotient, Pelagic fish, Western Indian Ocean

Capsule

Based on omega-3, fat, protein, and mercury contents, most fish bycatch from tuna fisheries would be good food sources to reduce nutritional insecurity for local populations.

1. Introduction

Commercial fisheries generate different levels of bycatch (i.e. incidental catch of non-targeted fish), accounting for a global annual estimate of discards larger than nine million metric tons (Pérez-Roda et al., 2019; Zeller et al., 2018). The reduction of fish discards has become a global concern over the last decades as high discarding mortality can play an important role in population and biodiversity decline (Gilman, 2011; Viana et al., 2013). Furthermore, discarding constitutes a substantial waste of food while the consumption of fish bycatch may reduce food insecurity, particularly in developing and least-developed coastal countries (Bell et al., 2015; Pilling et al., 2020). Consequently, many countries have implemented public policies to enforce the landing of fishing discards over the last decade although the outcomes of such policies remain debated (e.g., Sardà et al., 2015).

Global high seas fisheries targeting tuna and tuna-like species produce substantial bycatch, with about 170,000 and 100,000 metric tons discarded annually by longline and purse seine fisheries, respectively (Fonteneau et al., 2013; Hall et al., 2017). Although non-targeted small oceanic tunas and neritic tunas constitute the bulk of the purse seine bycatch across all ocean basins, bycatch is also composed of a highly diverse assemblage of > 50 edible fish species from several families, predominated by Istiophoridae, Carangidae, Balistidae, Coryphaenidae, Scombridae, and Carcharhinidae (Lezama-Ochoa et al., 2015; Torres-Irineo et al., 2014). In the western Indian Ocean, recent discard rates derived from fisheries observer programs suggest the total bycatch of these species could vary around 8,000 and 10,000 metric tons annually (Ruiz Gondra et al., 2018). Following the ban on discards of non-target fish caught with purse seine that entered into force in January 2018 (IOTC Resolutions 17/04 and 19/05), most fish bycatch from the western Indian Ocean tuna fishery are now landed in Port Victoria, Seychelles, where they are (i) mostly transhipped in containers for export to African and Asian countries and further processed (all species mixed), (ii) processed by local companies (e.g. smoked fish) for the most valuable species such as dolphinfishes (Coryphaenidae) and billfishes (Istiophoridae) for export, and (iii) locally consumed for the valuable species such as tripletail *Lobotes surinamensis*.

Fish is critical to food and nutrition security as the primary source of animal protein, especially in tropical countries and for coastal communities (Béné et al., 2015). Fish is also the most important source of essential fatty acids and a unique source of minerals, micronutrients often reported as deficient in the diets of vulnerable populations (Haddad et al., 2016; Hicks et al., 2019). Tropical countries mainly depend on small-scale coastal fisheries, which are highly impacted by overfishing and climate change (Bell et al., 2018; Dulvy and Allison, 2009; Robinson et al., 2020). Consumption of fish bycatch from industrial tropical tuna fisheries could then be a complementary or an alternative source of essential nutrients for tropical coastal communities (Bodin et al., 2017; Pilling et al., 2020). In the western Indian Ocean for instance, high levels of zinc and selenium have been reported in several istiophoriformes (Bodin et al., 2017; Kojadinovic et al., 2007), but information is still lacking regarding the content of fish bycatch from the tuna fisheries in other healthy nutrients such as essential fatty acids.

Omega-3 fatty acids such as eicosapentaenoic acid (EPA; 20:5n-3) and docosahexaenoic acid (DHA; 22:6n-3) have important human health benefits, including brain and retina development and coronary heart disease prevention (Swanson et al., 2012; FAO/WHO, 2010). Adequate dietary intake of omega-3 fatty acids is recommended due to inadequate biosynthesis capacities (Plourde and Cunnane, 2007). The most abundant natural dietary source of EPA and DHA is fish, especially pelagic fish (Gladyshev et al., 2018). Omega-6 fatty acids such as arachidonic acid (ARA; 20:4n-6) are also essential to human health, although they may be responsible for inflammation and cardiovascular diseases when present in excess (Mori and Hodgson, 2012). The omega-6 to omega-3 ratio could thus balance health outcomes (the lower the ratio the better) (Simopoulos, 2002) and is often considered in nutrition studies (e.g., Nišević et al., 2019; Strain et al., 2008). Mercury may also be a concern when investigating the nutritional value of fish. Indeed, mercury is neuro-, nephro-, and immunotoxic for humans in its methylated form (Bose-O'Reilly et al., 2010). Its content in most consumed fish should not exceed maximum limits of 1 $mg.kg^{-1}$ wet weight (ww) for large predatory fish and 0.5 $mg.kg^{-1}$ ww for other fish (FAO Codex Alimentarius Commission, 2011). Avoiding the consumption of fish because of mercury might however reduce its essential health benefits (Strain et al., 2008; Hu et al., 2017). In this context, a benefit-risk assessment appears essential to determine which fish species to consume and how much, in order to promote better health outcomes, i.e., to ensure adequate omega fatty acids intakes while minimizing exposure to mercury.

This study aimed to assess the nutritional value of 20 pelagic fish species belonging to 10 families and caught as bycatch in tropical tuna fisheries from the western Indian Ocean. We focused on their beneficial contents in proteins, fats and essential omega-3, and considered also the omega-6/omega-3 ratio and mercury content. The benefit-risk assessment used a hazard quotient for three people categories: young children, children and adults. The influence of fish length on the nutritional composition of muscle was also assessed.

2. Material and methods

2.1. Fish and tissue collection

Common fish bycatch from the western Indian Ocean were sampled between April and October 2018 (18 fishing dates/geographical positions). A total of 168 individuals from 18 species were collected during the unloading of purse seiners at Port Victoria, Seychelles, and complemented with seven billfishes (from two species) collected during the unloading of longliners. Fish length was measured with a caliper to the nearest cm: in lower-jaw-fork length for the Indo-Pacific sailfish *Istiophorus platypterus* and striped marlin *Tetrapturus audax*, in total length for silky shark *Carcharhinus falciformis*, tripletail *L. surinamensis*, unicorn leatherjacket *Aluterus monoceros*, and rough triggerfish *Canthidermis maculata*, and in fork length for all other species. Then, a piece of dorsal muscle (left side, under the fish dorsal spine) was sampled from each individual. Immediately after collection, samples were stored in cryotubes at -80°C at the Seychelles Fishing Authority Research Laboratory, Victoria, Seychelles, for several months before analysis.

2.2. Moisture

Moisture (i.e. water content) was used to convert concentrations from dry weight (dw) to wet weight (ww), as all biochemical analyses were performed on dry samples. The percentage of moisture was determined gravimetrically as the difference between wet and dry masses of samples after a 72-hour freeze drying using a Christ Alpha 1-2 LD plus lyophilizer. The mean analytical variability of the method was < 1%. After freeze-drying, samples were ground to a homogeneous powder with a ball mill and stored again at -80°C at the Seychelles Fishing Authority Research Laboratory, Victoria, Seychelles, for a month before subsequent analysis.

2.3. Crude protein content

Non-protein nitrogenous compounds found in high amounts in sharks (urea and trimethylamine oxide) were removed from an aliquot of silky shark dry powder with three distilled water rinses (Li et al., 2016). Aliquots of about 500 µg of dry powder (urea-free for silky shark and bulk for all other bycatch fish) were weighted to the nearest µg on an analytical balance, and analysed for nitrogen content by continuous flow on a Flash EA2000 elemental analyser (Thermo Fisher scientific) at the Pôle Spectrométrie Océan, University of Brest, France. The analytical variability of the method was 0.1%, based on reference material checked every six samples (acetanilide;

nitrogen content = 10.3%). Nitrogen content was converted into crude protein using a conversion factor of 5.58 adapted to fish muscle (Mariotti et al., 2008). Crude protein content was expressed in $mg.g^{-1}$ ww.

2.4. Fatty acids and total fat content

Aliquots of dry bulk powders were treated as described in Sardenne et al. (2019). Lipids were extracted from ca. 100 mg of powder with 6 mL of the modified Folch mixture directly added into glass vials. Extracts were flushed with gas nitrogen, vortexed, sonicated, and stored over 24 hours at -20°C. Tricosanoic acid (23:0; 2.3 µg) was added as internal standard to 1 mL of lipid extract. Lipids were transesterified with 800 µL of H_2SO_4 (3.8 % in MeOH) at 100°C for 10 min then washed with hexane-saturated distilled water. Fatty acid methyl esters (FAME) were separated and quantified on a Varian CP8400 gas chromatograph equipped with a Zebron ZB-WAX and a ZB-5HT column (both 30 m length, 0.25 mm internal diameter, 0.25 µm film thickness; Phenomenex) and a flame ionisation detector at the Lipidocean facility, University of Brest, France. Samples (2 µL) were injected in splitless mode at 280°C and carried by hydrogen gas. The oven temperature was raised from 60°C to 150°C at $50°C.min^{-1}$, to 170°C at $3.5°C.min^{-1}$, to 185°C at $1.5°C.min^{-1}$, to 225°C at $2.4°C.min^{-1}$ and then to 250°C at $5.5°C.min^{-1}$. FAME were identified by comparing sample retention times to those of commercial standard mixtures (37-component FAME mix and PUFA no. 1 and 3 mix; Supelco) on both columns using Galaxie 1.9.3.2 software (Varian). The mean analytical variability of the method was 8.1%, based on Supelco 37-component FAME mix routinely checked. FAME content was converted into fatty acids content. Total fat content was calculated as the sum of individual fatty acids, and expressed in TAG-equivalents using WHO conversion factors (Ratnayake, 2018). Individual fatty acids contents and total fat content were expressed in $mg.g^{-1}$ ww. Omega-6/omega-3 ratio is unitless.

2.5. Total mercury content (THg)

Aliquots of all dry bulk powders (10–50 mg dw) were analysed in duplicate (n=336) by thermal decomposition, gold amalgamation and atomic absorption detection (DMA-80, Milestone, Italy) at the Seychelles Fishing Authority Research Laboratory, Victoria, Seychelles. Calibration blanks were run in between each sample to ensure THg levels were reset to 0.1 ng. Analytical performance was checked every 15–20 samples against two laboratory control analyses (performed on large homogenized samples of white muscle and liver from *Thunnus obesus*, THg

= 0.141±0.004 and 0.986±0.036 mg.kg^{-1}, respectively) and the certified reference material, tuna fish flesh homogenate (IAEA-436; THg = 4.19±0.39 mg.kg^{-1}) (Bodin et al., 2017). Satisfactory accuracy (97–104%) was calculated with an analytical variability below 5% (n = 29). Limits of quantification were calculated from blank measurements, with THg values of 0.0016 ppm (i.e. µg.g^{-1}). The results (means of duplicate values) were reported in ppm ww. Note the contribution of methylmercury to total mercury is about 80-100% in most marine fish, depending on species, size, age and diet (EFSA, 2012a).

2.6. Data analysis

2.6.1. Hazard quotient calculation

Benefit-risk ratio, or hazard quotient (HQ), was computed for all individuals based on the equation of Gladyshev et al. (2009). HQ was already applied for several fish species (e.g., Anishchenko et al., 2017; Briones and Lazaro-Llanos, 2016; Razavi et al., 2014) and is computed as follows:

$$HQ = \frac{R_{EFA} \times c}{C \times RfD \times W}$$

where R_{EFA} (mg.d^{-1}), for Reference dose for essential fatty acids, is the daily dose recommended for EPA+DHA for a human person according to the sanitary agencies, c (µg.g^{-1}) is the mercury content for a given fish, C (mg.g^{-1}) is the EPA+DHA content for a given fish, RfD (µg.kg.d^{-1}), for oral Reference Dose, is the maximum tolerable daily intake of mercury according to the sanitary agencies, and W (kg) is the average weight of the human group of interest.

HQ parameters were set based on FAO/WHO and European Food Safety Agency (EFSA) recommendations, for three weight/age classes corresponding to young children (2–4 y), children (4–10 y), and adults (> 10 y) (Table 1). ‘Adults’ category includes pregnant and lactating females. EFSA aligned with WHO recommendations for EPA+DHA intakes but lowered the tolerable intake of methylmercury for a conservative reason, set to 1.3 µg.kg.week^{-1} (expressed as mercury) (i.e., 0.186 µg.kg.d^{-1}) for all age classes (EFSA, 2014; FAO/WHO 2010). EFSA default values were used for the average body weight of the age classes (EFSA, 2012b). The parameters setup used for HQ calculation are presented in Table 1, for R_{EFA}, RfD and W, and in Table 2 for c and C (fish contents in EPA+DHA and mercury). HQ is unitless and has the advantage to be independent from the servings size, as it is only based on the recommendation limits of sanitary agencies for good health. HQ > 1 means the consumption benefit is lower than the risk, and HQ < 1 means the consumption benefit is greater than the risk. A nutritional rating was attributed to each species based on HQ values: 'Best alternative' when all individuals have HQ < 1, 'Good alternative' when the average HQ < 1 but the range includes individuals with HQ > 1, 'Acceptable alternative' when the average HQ > 1 but the range includes individuals with HQ < 1, and 'Not advisable' when all individuals have HQ > 1.

2.6.2. Influence of species and fish length

First, correlations among fish length, THg, EPA+DHA, fat and protein contents, and omega-6/omega-3 ratio were investigated across the entire dataset (n = 175) using Spearman's rank correlation, with ϱ the correlation coefficient. Then, the effects of species, fish length, and their interactions on the variability (i.e. variance) in fat, protein, THg, EPA+DHA contents, omega-6/omega-3 ratio, and HQ were tested with F-tests. For HQ, only one age/weight category was considered as the results would be identical for the three categories. All data were log-transformed to improve normality. Normality and homogeneity of the variance were checked on model residuals, with Shapiro and Breush-Pagan tests, respectively. Despite transformation, residuals from all datasets did not reach normality but they were homogeneous. ANOVAs were applied on the multiple regression models, as it is robust to normality violation. Simple linear regressions were used to refine variability with fish length.
Data analyses were performed using R software 3.5.0 (R Core Team, 2016). All results are reported as means ± standard deviation.

3. Results

3.1. Correlations among nutritional contents

Across the entire dataset, the strongest positive correlations were observed between fat and EPA+DHA contents (ϱ = 0.86, p < 0.001) and between THg content and fish length (ϱ = 0.71, p < 0.001), then between EPA+DHA content and omega-6/omega-3 ratio (negative correlation, ϱ = -0.58, p < 0.001), and between THg and protein contents (positive correlation, ϱ = 0.55, p < 0.001) (Fig. 1). A weak negative correlation was obtained between omega-6/omega-3 ratio and protein content (ϱ = -0.46, p < 0.001). No relationship was observed between THg and fat contents (ϱ = 0.02, p = 0.835), and THg content and omega-6/omega-3 ratio (ϱ = -0.14, p = 0.08).

3.2. Variability in fat and protein contents and omega-6/omega-3 ratio

Variability in total fat and protein contents was mainly observed among species (Table 2). Species explained 82% of the variability in protein content (*df* = 19, F = 39.5, p < 0.001), with the highest protein contents observed for neritic tunas (231±5 $mg.g^{-1}$ and 223±12 $mg.g^{-1}$ for frigate tuna and kawakawa, respectively) and the lowest for batfishes and unicorn leatherjacket (155±6 $mg.g^{-1}$ and 162±7 $mg.g^{-1}$, respectively). Similarly, species explained 51% of the variability in fat content (*df* = 19, F = 12.2, p < 0.001), and the interaction between species and fish length explained 15% (*df* = 19, F = 3.6, p < 0.01). The highest fat contents were observed for neritic tunas (0.29±0.01 $mg.g^{-1}$ for both species), and the lowest for tripletail, unicorn leatherjacket, and batfishes (from 0.22±0.01 $mg.g^{-1}$ to 0.23±0.01 $mg.g^{-1}$) (Table 2). Species explained 82% of the variability in omega-6/omega-3 ratio (*df* = 19, F = 55.0, p < 0.001), with omega-6/omega-3 ratio < 1 for all teleost species but 2.6±1.4 for silky shark (Table 2), and the interaction between species and fish length explained 7% (*df* = 19, F = 5.0, p < 0.001).

3.3. Variability in mercury and omega-3 contents

Species was the main source of variability for both THg and EPA+DHA contents, i.e. it explained 71% and 76% of the variability, respectively. Fish length explained 10% and 1% of the variability for THg and EPA+DHA contents, respectively, and the interaction between species and fish length explained 6% of the variability for both THg and EPA+DHA contents (Table 3). The highest THg contents were obtained for silky shark (0.167±0.073 ppm ww), the three Istiophoridae species, in particular great barracuda (0.277±0.056 ppm ww), and for Scombridae, in particular kawakawa (0.152±0.068 ppm ww). The lowest contents were obtained for batfishes (0.005±0.002 ppm ww), unicorn leatherjacket (0.007±0.004 ppm ww) and the two Kyphisidae species (0.007±0.010 ppm ww). THg content increased with fish length in seven fish species, and especially in kawakawa (from 0.021 to 0.263 ppm ww, for specimens ranging between 23 and 55 cm in fork length; slope of 16%). For rough triggerfish, common dolphinfish, frigate tuna, tripletail, rainbow runner, and cottonmouth jack, the increase of THg content over the studied range sizes (i.e. slope) was < 1% (Fig. 2).

The contribution of EPA+DHA to total omega-3 ranked from 82±3% in silky shark to 96±1% in wahoo. After DHA and EPA, the third main omega-3 was 22:5n-3 (docosapentaenoic acid), which contributed to 5.9±3.8% of total omega-3 (0.09±0.08 $mg.g^{-1}$ ww in average for the whole dataset, n=175). The highest contents in EPA+DHA were obtained for striped marlin (3.12±2.84 $mg.g^{-1}$ ww), kawakawa (2.64±1.48 $mg.g^{-1}$ ww), Indo-Pacific sailfish (1.79±0.61 $mg.g^{-1}$ ww), and frigate tuna (1.77±0.74 $mg.g^{-1}$ ww), and for some Carangidae, especially cottonmouth jack

(1.76±0.69 mg.g^{-1} ww). The lowest EPA+DHA contents were observed for silky shark (0.19±0.13 mg.g^{-1} ww) and tripletail (0.80±0.20 mg.g^{-1} ww) (Table 3). EPA+DHA contents increased with fish length in cottonmouth jack (from 0.97 mg.g^{-1} ww at 21 cm to 3.29 mg.g^{-1} ww at 34 cm; slope of 14%), wahoo (from 0.87 mg.g^{-1} ww at 79 cm to 1.14 mg.g^{-1} ww at 105 cm; slope of 1%), and silky shark (from 0.19 mg.g^{-1} ww at 64 cm to 0.43 mg.g^{-1} ww at 91 cm; slope < 1%) (Fig. 2).

3.4. Variability in hazard quotient

HQ values varied mainly with species (74% of explained variability) and to a lesser extent with fish length (5% of explained variability), and species-fish length interaction (6% of explained variability) (Table 3). Overall, HQ values were the highest for silky shark (84±64, 56±43, and 29±22 for young children, children and adults, respectively) and the lowest for batfish (HQ < 0.4) and blue sea chub (HQ < 0.6) (Fig. 3). Eight species had a greater benefit than risk (average HQ < 1) for the three population categories, with similar HQ values (unicorn leatherjacket, flat needlefish, batfishes, pompano dolphinfish, blue sea chub, brassy chub, cottonmouth jack, and longfin yellowtail), while nine species always had a lower benefit than risk (silky shark > great barracuda > Indo-Pacific sailfish > wahoo > tripletail > striped marlin > kawakawa > frigate tuna > common dolphinfish) (Fig. 3). HQ values increased with fish length and always exceeded 1 in the largest sizes for five species: rough triggerfish, common dolphinfish, frigate tuna, tripletail, and Indo-Pacific sailfish (Fig. 4). In contrast, HQ values decreased with length in striped marlin mainly due to the increase in EPA+DHA content (not significant); this result however must be taken with caution in view of the low number of specimens (n = 3) and low size range (min-max fork length = 180-186 cm). Based on range and average values of HQ for adults, eight fish species were ranked as ‘Best alternative’, four as ‘Good alternative’, six as ‘Acceptable alternative’ and two were ‘Not advisable’ (Fig. 3). ‘Best alternative’ was attributed to four species (batfishes, blue sea chub, unicorn leatherjacket, and flat needlefish) for young children (Fig. 3).

4. Discussion

Twenty species of fish bycatch from the western Indian Ocean tropical tuna fisheries were analysed for moisture, protein, fat, fatty acid (omega-3 and omega-6) and mercury contents, and a benefit-risk evaluation based on hazard quotients was conducted. Despite high interspecies variability, all species are excellent protein sources (min–max = 14.4–25.2 g/100g fillet), low total fat sources (min–max = 0.2–2.4 g/100g fillet), low to good sources of omega-3 (min–max = 10–730 mg/100g fillet), and are relatively low in total mercury (min–max = 0.003–0.317 ppm ww). Striped marlin was the richest species in both fats and omega-3, frigate tuna was the richest species in proteins, and great barracuda the most contaminated with mercury. Based on hazard quotients for adults, 12 species were ranked best or good nutritional alternatives, while two species, the silky shark and the great barracuda, were not advisable for consumption. Six species were ranked as acceptable alternatives and should be considered in priority for complementary nutrition studies. Hazard quotients increased with fish length in five species, mainly due to increasing mercury contents with length.

4.1. Nutritional composition of fish bycatch from the tropical tuna fisheries in the western Indian Ocean

Across the entire dataset, no individual had mercury content above the maximum limits of 1 and 0.5 ppm ww defined by sanitary agencies for large fish and other fish, respectively. The most contaminated species (Istiophoridae and silky shark) were high order predators with trophic levels > 4.3 (FishBase, 2019), while the less contaminated were herbivorous (Kyphosidae) or first order predators (unicorn leatherjacket and batfishes) with trophic levels from 2.0 to 3.8 (FishBase, 2019). A positive relationship between mercury contamination and trophic position was indeed highlighted for several species from the Seychelles Exclusive Economic Zone (EEZ) (Bodin et al., 2017; Sardenne et al., 2017) due to mercury biomagnification in food webs (Kidd et al., 2011). However, the trophic position alone does not explain the mercury contamination of a species. Mercury content also increases with individual fish length, as previously measured in the western Indian Ocean for some of the studied species (Bodin et al., 2017; Kojadinovic et al., 2007). The low contamination of the common dolphinfish in the present study is more likely related to the small-sized individuals analysed (fork length = 42–71 cm, THg = 0.011–0.078 ppm ww, n = 13) and may not be representative of the overall THg range for this bycatch species caught by purse-seiners in the region. First, average size for common dolphinfish caught as bycatch is 80±20 cm, with individuals larger than 100 cm commonly observed in the fishery (SFA, unpublished data); secondly, largest individuals of dolphinfish targeted by longliners were around 4 and 6 times more contaminated in Seychelles EEZ (fork length = 92–106 cm, THg = 0.177±0.043 ppm, n = 10; Bodin et al., 2017) and Mozambique Channel (fork length=100–115 cm, THg=0.245±0.230 ppm, n=5; Kojadinovic et al., 2007), respectively. The same issue might occur for silky shark, rainbow runner, and wahoo for each of which our samples might not well reflect the maximum levels of contamination expected from the consumption of larger individuals caught in the fishery. The highest mercury content was however obtained for great barracuda (0.277±0.056 ppm ww) with body length close to the average length measured for this species in the purse seine tuna fishery (92±18 cm; SFA, unpublished data), suggesting the observed contamination level might be representative for the species in the fishery. While all studied species are pelagic, differences in habitat use (e.g. coastal, neritic, epipelagic) can also affect mercury contamination, as found for several large pelagic fish (Choy et al., 2009). Structure of the planktonic food web can also influence mercury contamination in fish, since lower trophic levels (e.g. organic matter, invertebrate species such copepods) can be contaminated by mercury at different levels (Kainz et al., 2008; Signa et al., 2019), as well as fish age: regardless of size, older fish are generally more contaminated than their younger congeners (van der Velden et al., 2012).

This study provides baseline values for the western Indian Ocean as data on omega-3, DHA, and EPA contents were scarce for the studied species in the area, especially data expressed in concentrations. Overall, our values of EPA+DHA contents are within the medium range reviewed by Gladyshev et al. (2018) for 172 species which ranked from 0.1 to 25.6 $mg.g^{-1}$ ww, the highest contents being generally obtained for Clupeiformes. Fish phylogeny and eco-morphology seem indeed the two main factors explaining variability in EPA+DHA contents (Gladyshev et al., 2018). Among the 10 families studied here, Istiophoridae and Scombridae generally contained more EPA and DHA than the other families. However, in comparison to other world regions, most studied species had lower EPA and DHA contents. Higher contents in EPA and DHA were found for coastal frigate tuna from Philippines, eastern Indian Ocean, with 1.1±0.0 and 3.9±0.3 $mg.g^{-1}$ ww (n=3) *vs.* 0.2±0.1 and 1.6±0.7 $mg.g^{-1}$ ww here, respectively (Briones and Lazaro-Llanos, 2016). These differences might be related to the location of the sampled tissue: tuna dorsal muscle analysed in our study is leaner than the ventral one (total muscle was analysed in the Philippines) (Nakamura et al., 2007). EPA and DHA contents for the common dolphinfish were similar to those obtained in the United States of America (unspecified ocean) by Cladis et al. (2014): 0.2±0.1 and 1.4±0.4 $mg.g^{-1}$ ww (n = 11) *vs.* 0.1±0.0 and 1.0±0.2 $mg.g^{-1}$ ww in the present study, although the species was leaner in the present study (fat content of 8.5±2.5 *vs.* 3.3±0.6 $mg.g^{-1}$ ww here). Wahoo contained less EPA and DHA in the present study than in the eastern Pacific: 0.1±0.0 and 0.9±0.1 $mg.g^{-1}$ ww *vs.* 0.5±0.2 and 3.6±1.6 $mg.g^{-1}$ ww (n = 2), respectively (Cladis et al., 2014). The same trend was observed for tripletail from Mexico, western Atlantic ocean, with EPA and DHA contents of 0.7 and 3.2 *vs*. 0.1 and 0.7 $mg.g^{-1}$ ww in the present study (Castro-González et al., 2013). These differences among areas could stem from partial oxidation during on-board storage, differences in method among laboratories (e.g. location of muscle sample, analytical differences), and/or differences related to species' ecological and biological factors such as habitat, season, and reproductive status. Variability in EPA and DHA proportions (in %) and omega-6/omega-3 ratio were indeed observed with season in tuna species from the western Indian Ocean which co-occur with the studies species (Dhurmeea et al., 2020; Sardenne et al., 2016). EPA and DHA are mainly produced by diatoms and dinoflagellates at the food webs basis and their proportions in tuna were correlated to sea surface temperature (Dhurmeea et al., 2020; Pethybridge et al., 2015). Due to global climate change, the omega-3 production at the food webs basis is predicted to be reduced by ca. 8% and 28% for EPA and DHA, respectively (Hixson and Arts, 2016). Phytoplankton communities have already changed in the northwest of the Indian Ocean with a reduction of diatoms biomass during winter, eventually impacting the composition of higher trophic level species (Do Rosário Gomes et al., 2014). In this context, the composition in macronutrients and micronutrients of fish should be routinely monitored to ensure adequate recommendations in terms of fish consumption.

4.2. Fish bycatch consumption recommendations based on hazard quotients

Hazard quotients (HQ) based on mercury and EPA+DHA contents were highly variable among species. Highest HQ were obtained for the top predators (silky shark and great barracuda in particular) and often for the largest individuals, due to an increase in mercury content with fish size/age in several species (see previous section). Silky shark was found with very low omega-3 contents (i.e. the daily serving portion required to supply 300 mg of EPA+DHA would be 1.6 kg, which would lead to a mercury consumption of 268 µg). For these reasons, benefit is lower than risk for the consumption of these species. Eight species were ranked as 'Best alternative' or 'Good alternative' for the three people categories: batfishes, brassy chub, blue sea chub, unicorn leatherjacket, cottonmouth jack, flat needlefish, longfin yellowtail, and pompano dolphinfish. Among them, cottonmouth jack was lipid-rich (about 10 $mg.g^{-1}$ ww) and flat needlefish was protein-rich (about 198 $mg.g^{-1}$ ww). Based on mercury and EPA+DHA contents, these two species can be particularly recommended for human consumption, especially for young children and children, with respective daily serving portions of 85 g and 142 g (cottonmouth jack) and 117 g and 196 g (flat needlefish) (Table 4). Other species, such as pompano dolphinfish and brassy chub are also good food sources, especially for adults as some individuals can have higher risk than benefit (daily serving portion between 99 g and 264 g according to people category and fish species; Table 4). The consumption of species ranked ‘Not advisable’ (Fig. 3) should not be daily, especially for young children, children, and pregnant women, as prenatal exposure to mercury might affect children development (Nišević et al., 2019).

4.3. Caveats about hazard quotient and recommendations

For the benefit-risk assessment to be complete, other positive and negative nutritional components must be included in the HQ calculation: e.g. essential nutrients such iodine and selenium, but also organic contaminants such dioxins-like compounds, and toxins such as ciguatera. For instance, selenium, a mineral constituting proteins involved in the antioxidant system, might be important to balance the negative effects of mercury on health (Ralston et al., 2016), but this potential remediation remain to be confirmed (Gerson et al., 2020). In contrast, ciguatera poisoning was reported for some of the studied species, caught from Atlantic and Pacific Oceans: e.g. ciguatera toxins were found in blue sea chub from French Polynesia (57% of 29 tested fish; Gaboriau et al., 2014) and in longfin yellowtail and wahoo from Canary islands (17% of 793 tested fish and 3% of 32 tested fish, respectively; Sanchez-Henao et al., 2019). The consumption of these species from the western Indian Ocean should thus be cautious until the risks are fully evaluated. Persistent organic pollutants were found in relatively low levels in swordfish and tuna from the western Indian Ocean, except for fishes from the Mozambique Channel which showed higher dichlorodiphenyltrichloroethane levels (DDT; Munschy et al., 2020). An evaluation of these pollutants in fish bycatch from tropical tuna fisheries would also be useful to improve the consumption recommendations.

WHO states adequate intakes for EPA+DHA are 250-2000 mg.day^{-1}, while specifying there is no evidence of gain for health to consume 2000 mg.day^{-1}, unless for secondary prevention of coronary health disease (FAO/WHO, 2010). HQ calculation was set on EFSA and WHO optimum recommendations (300 mg.day^{-1} for adults, but see Nagasaka et al., 2014) because an unnecessary increase in fish consumption of ca. 6 fold would not be sustainable for fish stocks, most of them being already fully exploited or overfished worldwide (Link and Watson, 2019; Worm et al., 2006). Such an increase in fishing effort would be particularly counterproductive as overfishing, in association with climate change, has been shown to increase mercury content in predator fish by causing dietary shifts (Schartup et al., 2019). The best option to obtain DHA and EPA from marine fisheries would be to increase by-product utilization and reduce food waste (Hamilton et al., 2020). Assessing the risks and benefits associated with the consumption of fisheries bycatch is a step in this direction.

Conclusion

Every year, more than 10,000 metric tons of edible fish species are landed in the Seychelles as bycatch of tuna fisheries, with little or no value. However, most of these species were found to be good sources of nutrients (omega-3, fat and protein contents) and little exposed to mercury. Among the 20 studied species, silky shark and great barracuda should be consumed with moderation, while eight species (batfishes, brassy chub, blue sea chub, unicorn leatherjacket, cottonmouth jack, flat needlefish, longfin yellowtail, and pompano dolphinfish) were classified as best alternative. Those species would be good food sources to reduce nutritional insecurity for local populations, including for young children. Evaluation and monitoring on further contaminants, toxins and micronutrients would be useful to strengthen the consumption recommendations.

Acknowledgments

The authors thank all fishermen and crews of the fishing compagnies CFTO and SAPMER who gave the fish, observers who assisted with fish sampling, and the Research section of the Seychelles Fishing Authority for using the wet laboratory during fish processing. We also thank two anonymous reviewers for their comments on an earlier draft of this work. The present work is a contribution to the SEYFISH project led by the Seychelles Fishing Authority (SFA), with the financial support of the French Research Institute for Sustainable Development (IRD) and the European Fisheries Partnership Agreement (EU-FPA). The Regional Council of Brittany, France (SAD program) is acknowledged for its support to F. Sardenne.

Author contributions

Fany Sardenne: methodology, software, validation, investigation, writing – original draft. Nathalie Bodin: conceptualization, methodology, investigation, resources, data curation, validation, writing – review & editing, supervision, funding acquisition. Anaïs Médieu: investigation, writing – review & editing. Marisa Antha: investigation. Rona Arrisol: investigation. Fabienne Le Grand: validation, resources. Antoine Bideau: investigation. Jean-Marie Munaron: investigation. François Le Loc'h: validation, investigation - review & editing.

Emmanuel Chassot: writing – review & editing.

References

Anishchenko, O.V., Sushchik, N.N., Makhutova, O.N., Kalachova, G.S., Gribovskaya, I.V., Morgun, V.N., Gladyshev, M.I., 2017. Benefit-risk ratio of canned pacific saury (*Cololabis saira*) intake: Essential fatty acids vs. heavy metals. Food Chem. Toxicol. 101, 8–14. https://doi.org/10.1016/j.fct.2016.12.035

Bell, J.D., Allain, V., Allison, E.H., Andréfouët, S., Andrew, N.L., Batty, M.J., Blanc, M., Dambacher, J.M., Hampton, J., Hanich, Q., Harley, S., Lorrain, A., McCoy, M., McTurk, N., Nicol, S., Pilling, G., Point, D., Sharp, M.K., Vivili, P., Williams, P., 2015. Diversifying the use of tuna to improve food security and public health in Pacific Island countries and territories. Mar. Policy 51, 584–591. https://doi.org/10.1016/j.marpol.2014.10.005

Bell, J.D., Cisneros-Montemayor, A., Hanich, Q., Johnson, J.E., Lehodey, P., Moore, B.R., Pratchett, M.S., Reygondeau, G., Senina, I., Virdin, J., Wabnitz, C.C.C., 2018. Adaptations to maintain the contributions of small-scale fisheries to food security in the Pacific Islands. Mar. Policy 88, 303–314. https://doi.org/10.1016/j.marpol.2017.05.019

Béné, C., Barange, M., Subasinghe, R., Pinstrup-Andersen, P., Merino, G., Hemre, G.I., Williams, M., 2015. Feeding 9 billion by 2050 – Putting fish back on the menu. Food Secur. 7, 261–274. https://doi.org/10.1007/s12571-015-0427-z

Bodin, N., Lesperance, D., Albert, R., Hollanda, S.J., Michaud, P., Degroote, M., Churlaud, C., Bustamante, P., 2017. Trace elements in oceanic pelagic communities in the western Indian Ocean. Chemosphere 174, 354–362. https://doi.org/10.1016/j.chemosphere.2017.01.099

Bose-O'Reilly, S., McCarty, K.M., Steckling, N., Lettmeier, B., 2010. Mercury exposure and children's health. Curr. Probl. Pediatr. Adolesc. Health Care. https://doi.org/10.1016/j.cppeds.2010.07.002

Briones, D.P., Lazaro-Llanos, N., 2016. Omega-3 fatty acids versus heavy metals: a quantitative estimation of the benefit-risk ratio for the consumption of commonly-consumed fish and products in Metro, Manila. KIMIKA 26, 39–50. https://doi.org/10.26534/kimika.v26i2.39-50

Castro-González, I., Maafs-Rodríguez, A.G., Silencio-Barrita, J.L., Galindo-Gómez, C., Pérez-Gil, F., 2013. Evaluation of the possible inclusion of certain fish species in chronic kidney disease diets based on their adverse and beneficial nutrient ratios. Int. J. Food Sci. Nutr. 64, 82–88. https://doi.org/10.3109/09637486.2012.700921

Choy, C.A., Popp, B.N., Kaneko, J.J., Drazen, J.C., 2009. The influence of depth on mercury levels in pelagic fishes and their prey. Proc. Natl. Acad. Sci. 106, 13865–13869. https://doi.org/10.1073/pnas.0900711106

Cladis, D.P., Kleiner, A.C., Freiser, H.H., Santerre, C.R., 2014. Fatty acid profiles of commercially available finfish fillets in the United States. Lipids 49, 1005–1018. https://doi.org/10.1007/s11745-014-3932-5

Dhurmeea, Z., Pethybridge, H., Langlais, C., Somes, C.J., Nikolic, N., Appadoo, C., Bodin, N., Studies, O., 2020. Spatial variation in stable isotopes and fatty acid trophic markers in albacore tuna (*Thunnus alalunga*) from the western Indian Ocean. Deep Sea Res. Part I Oceanogr. Res. Pap. 1–31.

Do Rosário Gomes, H., Goes, J.I., Matondkar, S.G.P., Buskey, E.J., Basu, S., Parab, S., Thoppil, P., 2014. Massive outbreaks of *Noctiluca scintillans* blooms in the Arabian Sea due to spread of hypoxia. Nat. Commun. 5, 1–8. https://doi.org/10.1038/ncomms5862

Dulvy, N., Allison, E., 2009. A place at the table? Nat. Clim. Chang. 1, 68–70. https://doi.org/10.1038/climate.2009.52

EFSA, 2012a. Scientific Opinion on the risk for public health related to the presence of mercury and methylmercury in food. EFSA J. 10, 2985.

EFSA, 2012b. Guidance on selected default values to be used by the EFSA Scientific Committee, Scientific Panels and Units in the absence of actual measured data. EFSA J. 10,2579. https://doi:10.2903/j.efsa.2012.2579.EFSA, 2014. Scientific Opinion on health benefits of seafood (fish and shellfish) consumption in relation to health risks associated with exposure to methylmercury. EFSA J. 12, 3761. https://doi.org/10.2903/j.efsa.2014.3761

FAO Codex Alimentarius Commission, 2011. Working document for Information and use in discussion related to contaminants and toxins in the GSCTFF, Joint FAO/WHO Food Standards Programme Codex Committee on Contaminants in Foods. Rome, Italie. https://doi.org/10.3768/rtipress.2014.rb.0007.1405

FAO/WHO, 2010. Report of the Joint FAO/WHO Expert Consultation on the Risks and Benefits of Fish Consumption. Rome, 25-29 january 2010. Rome.

FAO, I.O.T.C., 2019. RESOLUTION 19/05 On a ban on discards of bigeye tuna, skipjack tuna, yellowfin tuna, and non- targeted species caught by purse seine vessels in the iotc area of competence. https://iotc.org/cmm/resolution-1905-ban-discards-bigeye-tuna-skipjack-tuna-yellowfin-tuna-and-non-targeted-species

Fonteneau, A., Chassot, E., Bodin, N., 2013. Global spatio-temporal patterns in tropical tuna purse seine fisheries on drifting fish aggregating devices (DFADs): Taking a historical perspective to inform current challenges. Aquat. Living Resour. 26, 37–48.

Froese, R., Pauly, D., 2019. FishBase [WWW Document]. World Wide Web Electron. Publ. URL www.fishbase.org, version

Gaboriau, M., Ponton, D., Darius, H.T., Chinain, M., 2014. Ciguatera fish toxicity in French Polynesia: Size does not always matter. Toxicon 84, 41–50. https://doi.org/10.1016/j.toxicon.2014.03.006

Gerson, J.R., Walters, D.M., Eagles-Smith, C.A., Bernhardt, E.S., Brandt, J.E., 2020. Do two wrongs make a right? Persistent uncertainties regarding environmental Selenium–Mercury interactions. Environ. Sci. Technol. 54, 9228–9234. https://doi.org/10.1021/acs.est.0c01894

Gilman, E.L., 2011. Bycatch governance and best practice mitigation technology in global tuna fisheries. Mar. Policy 35, 590–609. https://doi.org/10.1016/J.MARPOL.2011.01.021

Gladyshev, M.I., Sushchik, N.N., Anishchenko, O. V., Makhutova, O.N., Kalachova, G.S., Gribovskaya, I. V., 2009. Benefit-risk ratio of food fish intake as the source of essential fatty acids vs. heavy metals: A case study of Siberian grayling from the Yenisei River. Food Chem. 115, 545–550. https://doi.org/10.1016/j.foodchem.2008.12.062

Gladyshev, M.I., Sushchik, N.N., Tolomeev, A.P., Dgebuadze, Y.Y., 2018. Meta-analysis of factors associated with omega-3 fatty acid contents of wild fish. Rev. Fish Biol. Fish. 28, 277–299. https://doi.org/10.1007/s11160-017-9511-0

Haddad, L., Hawkes, C., Waage, J., Webb, P., Godfray, C., Toulmin, C., 2016. Food systems and diets: Facing the challenges of the 21st century.

Hall, M., Gilman, E., Minami, H., Mituhasi, T., Carruthers, E., 2017. Mitigating bycatch in tuna fisheries. Rev. Fish Biol. Fish. 27, 881–908. https://doi.org/10.1007/s11160-017-9478-x

Hamilton, H.A., Newton, R., Auchterlonie, N.A., Müller, D.B., 2020. Systems approach to quantify the global omega-3 fatty acid cycle. Nat. Food 1, 59–62. https://doi.org/10.1038/s43016-019-0006-0

Hicks, C.C., Cohen, P.J., Graham, N.A.J.J., Nash, K.L., Allison, E.H., D'Lima, C., Mills, D.J., Roscher, M., Thilsted, S.H., Thorne-Lyman, A.L., MacNeil, M.A., 2019. Harnessing global fisheries to tackle micronutrient deficiencies. Nature 574, 95–98. https://doi.org/10.1038/s41586-019-1592-6

Hixson, S.M., Arts, M.T., 2016. Climate warming is predicted to reduce omega-3, long-chain, polyunsaturated fatty acid production in phytoplankton. Glob. Chang. Biol. 22, 2744–2755. https://doi.org/10.1111/gcb.13295

Hu, X.F., Laird, B.D., Chan, H.M., 2017. Mercury diminishes the cardiovascular protective effect of omega-3 polyunsaturated fatty acids in the modern diet of Inuit in Canada. Environ. Res.

152, 470–477. https://doi.org/10.1016/j.envres.2016.06.001

Kainz, M., Arts, M.T., Mazumder, A., 2008. Essential versus potentially toxic dietary substances: A seasonal comparison of essential fatty acids and methyl mercury concentrations in the planktonic food web. Environ. Pollut. 155, 262–270. https://doi.org/10.1016/j.envpol.2007.11.021

Kidd, K., Clayden, M., Jardine, T., 2011. Bioaccumulation and Biomagnification of Mercury through Food Webs, in: Environmental Chemistry and Toxicology of Mercury. John Wiley & Sons, Inc., Hoboken, NJ, USA, pp. 453–499. https://doi.org/10.1002/9781118146644.ch14

Kojadinovic, J., Potier, M., Le Corre, M., Cosson, R.P., Bustamante, P., 2007. Bioaccumulation of trace elements in pelagic fish from the Western Indian Ocean. Environ. Pollut., 146, 548–566. https://doi.org/10.1016/j.envpol.2006.07.015

Lamborg, C.H., Hammerschmidt, C.R., Bowman, K.L., Swarr, G.J., Munson, K.M., Ohnemus, D.C., Lam, P.J., Heimbürger, L.E., Rijkenberg, M.J.A., Saito, M.A., 2014. A global ocean inventory of anthropogenic mercury based on water column measurements. Nature 512, 65–68. https://doi.org/10.1038/nature13563

Lezama-Ochoa, N., Murua, H., Chust, G., Ruiz, J., Chavance, P., de Molina, A.D., Caballero, A., Sancristobal, I., 2015. Biodiversity in the by-catch communities of the pelagic ecosystem in the Western Indian Ocean. Biodivers. Conserv. 24, 2647–2671. https://doi.org/10.1007/s10531-015-0951-3

Li, Y., Zhang, Y., Hussey, N.E., Dai, X., 2016. Urea and lipid extraction treatment effects on δ^{15}N and δ^{13}C values in pelagic sharks. Rapid Commun. Mass Spectrom. 30, 1–8. https://doi.org/10.1002/rcm.7396

Link, J.S., Watson, R.A., 2019. Global ecosystem overfishing: Clear delineation within real limits to production. Sci. Adv. 5, eaav0474. https://doi.org/10.1126/sciadv.aav0474

Mariotti, F., Tomé, D., Mirand, P.P., 2008. Converting nitrogen into protein - Beyond 6.25 and Jones' factors. Crit. Rev. Food Sci. Nutr. 48, 177–184. https://doi.org/10.1080/10408390701279749

Médieu, A., Sabarros, P., P., Bodin, N., Chassot, E., Cauquil, P., Njaratiana, R., Bach, P., 2018. Biological and ecological traits of non-targeted species caught by the tuna purse seine fishery in the western Indian Ocean. IOTC–2018–WPEB14 1–16.

Mori, T.A., Hodgson, J.M., 2012. Fatty acids: Health effects of omega-6 polyunsaturated fatty acids, in: Encyclopedia of Human Nutrition. Elsevier Inc., pp. 209–214. https://doi.org/10.1016/B978-0-12-375083-9.00100-8

Munschy, C., Vigneau, E., Bély, N., Héas-Moisan, K., Olivier, N., Pollono, C., Hollanda, S., Bodin, N., 2020. Legacy and emerging Persistent Organic Pollutant (POP) levels and profiles in top predator fish from the western Indian Ocean in relation to their trophic ecology. Environ. Res. in press.

Nagasaka, R., Gagnon, C., Swist, E., Rondeau, I., Massarelli, I., Cheung, W., Ratnayake, W.M.N., 2014. EPA and DHA status of South Asian and white Canadians living in the National Capital Region of Canada. Lipids 49, 1057–1069. https://doi.org/10.1007/s11745-014-3942-3

Nakamura, Y.-N.N., Ando, M., Seoka, M., Kawasaki, K. ichi, Tsukamasa, Y., 2007. Changes of proximate and fatty acid compositions of the dorsal and ventral ordinary muscles of the full-cycle cultured Pacific bluefin tuna *Thunnus orientalis* with the growth. Food Chem. 103, 234–241. https://doi.org/10.1016/j.foodchem.2006.07.064

Nišević, J.R., Prpić, I., Kolić, I., Baždarić, K., Tratnik, J.S., Prpić, I.Š., Mazej, D., Špirić, Z., Barbone, F., Horvat, M., 2019. Combined prenatal exposure to mercury and LCPUFA on newborn's brain measures and neurodevelopment at the age of 18 months. Environ. Res. 178, 108682. https://doi.org/10.1016/j.envres.2019.108682

Pérez-Roda, A., Gilman, E., Huntington, T., Kennelly, S.J., Suuronen, P., Chaloupka, M., Medley, P., 2019. A third assessment of global marine fisheries discards, FAO Fisheries and Aquaculture Technical Paper. No. 633. FAO Fisheries and Aquaculture Technical Paper No. 633., Rome, Italy. http://www.fao.org/3/CA2905EN/ca2905en.pdf

Pethybridge, H.R., Parrish, C.C., Morrongiello, J., Young, J.W., Farley, J.H., Gunasekera, R.M., Nichols, P.D., 2015. Spatial patterns and temperature predictions of tuna fatty acids: tracing essential nutrients and changes in primary producers. PLoS One 10, e0131598. https://doi.org/10.1371/journal.pone.0131598

Pilling, G.M., Harley, S.J., Nicol, S., Williams, P., Hampton, J., 2020. Can the tropical Western and Central Pacific Tuna purse seine fishery contribute to Pacific Island population food security?, in: Food Security in Small Island States. Springer Singapore, pp. 133–156. https://doi.org/10.1007/978-981-13-8256-7_8

Plourde, M., Cunnane, S.C., 2007. Extremely limited synthesis of long chain polyunsaturates in adults: implications for their dietary essentiality and use as supplements. Appl. Physiol. Nutr. Metab. 32, 619–634. https://doi.org/10.1139/H07-034

R Core Team, 2016. R Development Core Team. R A Lang. Environ. Stat. Comput. 55, 275–286. https://doi.org/http://www.R-project.org

Ralston, N.V.C., Ralston, C.R., Raymond, L.J., 2016. Selenium health benefit values: updated criteria for mercury risk assessments. Biol. Trace Elem. Res. 171, 262–269. https://doi.org/10.1007/s12011-015-0516-z

Ratnayake, N., 2018. Protocol for measuring trans fatty acids in foods. WHO-2018. https://www.who.int/docs/default-source/documents/replace-transfats/a-food-analysis-lab-protocol.pdf?sfvrsn=b27e4111_2

Razavi, N.R., Arts, M.T., Qu, M., Jin, B., Ren, W., Wang, Y., Campbell, L.M., 2014. Effect of eutrophication on mercury, selenium, and essential fatty acids in Bighead Carp (*Hypophthalmichthys nobilis*) from reservoirs of eastern China. Sci. Total Environ. 499, 36–46. https://doi.org/10.1016/j.scitotenv.2014.08.019

Robinson, J.P.W., Robinson, J., Gerry, C., Govinden, R., Freshwater, C., Graham, N.A.J., 2020. Diversification insulates fisher catch and revenue in heavily exploited tropical fisheries. Sci. Adv. 6, eaaz0587. https://doi.org/10.1126/sciadv.aaz0587

Ruiz Gondra, J., Lopez, J., Abascal, F.J., Pascual Alayon, P.J., Amandè, M.J., Bach, P., Cauquil, P., Murua, H., Ramos Alonso, M.L., Sabarros, P.S., 2018. Bycatch of the European and associated flag purse-seine tuna fishery in the Indian ocean for the period 2008-2017, IOTC-2018-WPEB14-15, 15p

Sanchez-Henao, J.A., García-Álvarez, N., Fernández, A., Saavedra, P., Silva Sergent, F., Padilla, D., Acosta-Hernández, B., Martel Suárez, M., Diogène, J., Real, F., 2019. Predictive score and probability of CTX-like toxicity in fish samples from the official control of ciguatera in the Canary Islands. Sci. Total Environ. 673, 576–584. https://doi.org/10.1016/j.scitotenv.2019.03.445

Sardà, F., Coll, M., Heymans, J.J., Stergiou, K.I., 2015. Overlooked impacts and challenges of the new European discard ban. Fish Fish. 16, 175–180. https://doi.org/10.1111/faf.12060

Sardenne, F., Bodin, N., Chassot, E., Amiel, A., Fouché, E., Degroote, M., Hollanda, S., Pethybridge, H., Lebreton, B., Guillou, G., Ménard, F., 2016. Trophic niches of sympatric tropical tuna in the Western Indian Ocean inferred by stable isotopes and neutral fatty acids. Prog. Oceanogr. 146, 75–88. https://doi.org/10.1016/j.pocean.2016.06.001

Sardenne, F., Bodin, N., Metral, L., Crottier, A., Le Grand, F., Bideau, A., Brisset, B., Bourjea, J., Saraux, C., Bonhommeau, S., Kerzérho, V., Bernard, S., Rouyer, T., 2019. Effects of extraction method and storage of dry tissue on marine lipids and fatty acids. Anal. Chim. Acta 1051, 82–93. https://doi.org/10.1016/J.ACA.2018.11.012

Sardenne, F., Hollanda, S., Lawrence, S., Albert-Arrisol, R., Degroote, M., Bodin, N., 2017. Trophic structures in tropical marine ecosystems: a comparative investigation using three different ecological tracers. Ecol. Indic. 81, 315–324.

https://doi.org/10.1016/j.ecolind.2017.06.001

Schartup, A.T., Thackray, C.P., Qureshi, A., Dassuncao, C., Gillespie, K., Hanke, A., Sunderland, E.M., 2019. Climate change and overfishing increase neurotoxicant in marine predators. Nature. https://doi.org/10.1038/s41586-019-1468-9

Signa, G., Calizza, E., Costantini, M.L., Tramati, C., Sporta Caputi, S., Mazzola, A., Rossi, L., Vizzini, S., 2019. Horizontal and vertical food web structure drives trace element trophic transfer in Terra Nova Bay, Antarctica. Environ. Pollut. 246, 772–781. https://doi.org/10.1016/j.envpol.2018.12.071

Simopoulos, A.P., 2002. The importance of the ratio of omega-6/omega-3 essential fatty acids. Biomed. Pharmacother. 56, 365–379. https://doi.org/10.1016/S0753-3322(02)00253-6

Strain, J.J., Davidson, P.W., Bonham, M.P., Duffy, E.M., Stokes-Riner, A., Thurston, S.W., Wallace, J.M.W., Robson, P.J., Shamlaye, C.F., Georger, L.A., Sloane-Reeves, J., Cernichiari, E., Canfield, R.L., Cox, C., Huang, L.S., Janciuras, J., Myers, G.J., Clarkson, T.W., 2008. Associations of maternal long-chain polyunsaturated fatty acids, methyl mercury, and infant development in the Seychelles Child Development Nutrition Study. Neurotoxicology 29, 776–782. https://doi.org/10.1016/j.neuro.2008.06.002

Swanson, D., Block, R., Mousa, S.A., 2012. Omega-3 Fatty Acids EPA and DHA: Health Benefits Throughout Life. Adv. Nutr. 3, 1–7. https://doi.org/10.3945/an.111.000893

Torres-Irineo, E., Amandè, M.J., Gaertner, D., Molina, A.D. de, Murua, H., Chavance, P., Ariz, J., Ruiz, J., Lezama-Ochoa, N., de Molina, A.D., Murua, H., Chavance, P., Ariz, J., Ruiz, J., Lezama-Ochoa, N., 2014. Bycatch species composition over time by tuna purse-seine fishery in the eastern tropical Atlantic Ocean. Biodivers. Conserv. 23, 1157–1173. https://doi.org/10.1007/s10531-014-0655-0

Tremain, D.M., Adams, D.H., 2012. Mercury in groupers and sea basses from the gulf of mexico: Relationships with size, age, and feeding ecology. Trans. Am. Fish. Soc. 141, 1274–1286. https://doi.org/10.1080/00028487.2012.683232

van der Velden, S., Reist, J.D., Babaluk, J.A., Power, M., 2012. Biological and life-history factors affecting total mercury concentrations in Arctic charr from Heintzelman Lake, Ellesmere Island, Nunavut. Sci. Total Environ. 433, 309–317. https://doi.org/10.1016/j.scitotenv.2012.06.055

Viana, M., McNally, L., Graham, N., Reid, D.G., Jackson, A.L., 2013. Ignoring discards biases the assessment of fisheries' ecological fingerprint. Biol. Lett. 9, 20130812. https://doi.org/10.1098/rsbl.2013.0812

Worm, B., Barbier, E.B., Beaumont, N., Duffy, J.E., Folke, C., Halpern, B.S., Jackson, J.B.C., Lotze, H.K., Micheli, F., Palumbi, S.R., Sala, E., Selkoe, K.A., Stachowicz, J.J., Watson, R., 2006. Impacts of biodiversity loss on ocean ecosystem services. Science. 314, 787–790. https://doi.org/10.1126/science.1132294

Zeller, D., Cashion, T., Palomares, M., Pauly, D., 2018. Global marine fisheries discards: A synthesis of reconstructed data. Fish Fish. 19, 30–39. https://doi.org/10.1111/faf.12233

Table 1. Parameters setup for hazard quotient calculation, based on reference values from sanitary agencies (FAO/WHO and EFSA). R_{EFA} = Reference dose for essential fatty acids (EPA+DHA); RfD = oral Reference Dose for mercury. Adults and teens with body weight below 70 kg should be referred to children category. *arbitrary set to the upper range limit.

Categories	R_{EFA} ($mg.d^{-1}$)		Mercury RfD ($\mu g.kg.d^{-1}$)	Weight (kg)
	Optimum	Range		
Young children (2-4 y)	150*	100-150	0.186	12
Children (4-10 y)	250*	150-250	0.186	30
Adults & teens (> 10 y)	300	250-2000	0.186	70

Table 2. Nutritional composition of dorsal muscle for 20 bycatch fish species collected in the western Indian Ocean in 2018. Total fat is in triacylglycerol equivalents. DHA = docosahexaenoic acid (22:6n-3), EPA = Eicosapentaenoic acid (20:5n-3), ww = wet weight. See Material and Method section for the length measurement method of each species.

Family	Scientific name	English name	Code	n	Length (cm)	Mercury (ppm ww)	DHA ($mg.g^{-1}$ ww)	EPA ($mg.g^{-1}$ ww)	Omega 3 ($mg.g^{-1}$ ww)
					Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
Balistidae	*Canthidermis maculata*	Rough triggerfish	CNT	13	29.6 ± 3.3	0.028 ± 0.021	0.80 ± 0.15	0.18 ± 0.04	1.06 ± 0.16
Belonidae	*Ablennes hians*	Flat needlefish	BAF	4	87.0 ± 15.7	0.012 ± 0.004	1.18 ± 0.29	0.09 ± 0.03	1.40 ± 0.37
Carangidae	*Decapterus macarellus*	Mackerel scad	MSD	9	33.2 ± 3.4	0.030 ± 0.021	1.24 ± 0.28	0.19 ± 0.07	1.53 ± 0.39
	Elagatis bipinnulata	Rainbow runner	RRU	11	58.0 ± 13.0	0.054 ± 0.059	1.30 ± 0.24	0.21 ± 0.08	1.64 ± 0.36
	Seriola rivoliana	Longfin yellowtail	YTL	4	28.9 ± 5.5	0.021 ± 0.016	1.29 ± 0.20	0.18 ± 0.03	1.57 ± 0.24
	Uraspis secunda	Cottonmouth jack	USE	14	28.5 ± 3.5	0.018 ± 0.012	1.51 ± 0.56	0.24 ± 0.14	2.12 ± 0.96
Carcharhinidae	*Carcharhinus falciformis*	Silky shark	FAL	8	74.5 ± 9.8	0.167 ± 0.073	0.16 ± 0.12	0.02 ± 0.02	0.23 ± 0.17
Coryphaenidae	*Coryphaena equiselis*	Pompano dolphinfish	CFW	4	42.8 ± 3.8	0.019 ± 0.007	1.28 ± 0.26	0.23 ± 0.03	1.61 ± 0.28
	Coryphaena hippurus	Common dolphinfish	DOL	9	59.8 ± 9.1	0.043 ± 0.022	0.96 ± 0.22	0.11 ± 0.03	1.13 ± 0.26
Ephippidae	*Platax spp*	Batfishes	BAT	2	20.5 ± 7.8	0.005 ± 0.002	1.06 ± 0.30	0.25 ± 0.09	1.46 ± 0.46
Istiophoridae	*Istiophorus platypterus*	Indo-Pacific sailfish	SFA	4	188.0 ± 26.4	0.151 ± 0.101	1.60 ± 0.52	0.19 ± 0.09	1.94 ± 0.70
	Sphyraena barracuda	Great barracuda	GBA	2	88.0 ± 5.7	0.277 ± 0.056	0.98 ± 0.04	0.08 ± 0.02	1.13 ± 0.08
	Tetrapturus audax	Striped marlin	MLS	3	182.7 ± 3.1	0.130 ± 0.030	2.68 ± 2.32	0.44 ± 0.52	3.58 ± 3.21
Kyphosidae	*Kyphosus cinerascens*	Blue sea chub	KYC	11	23.3 ± 2.3	0.007 ± 0.002	1.13 ± 0.23	0.20 ± 0.05	1.58 ± 0.36
	Kyphosus vaigiensis	Brassy chub	KYV	21	26.9 ± 3.5	0.007 ± 0.010	0.96 ± 0.16	0.18 ± 0.04	1.33 ± 0.25
Lobotidae	*Lobotes surinamensis*	Tripletail	LOB	10	44.2 ± 7.9	0.061 ± 0.043	0.72 ± 0.19	0.08 ± 0.01	0.87 ± 0.22
Monacanthidae	*Aluterus monoceros*	Unicorn leatherjacket	ALM	10	39.2 ± 6.7	0.007 ± 0.004	0.78 ± 0.07	0.15 ± 0.04	0.99 ± 0.07
Scombridae	*Acanthocybium solandri*	Wahoo	WAH	5	94.4 ± 10.7	0.086 ± 0.046	0.91 ± 0.13	0.11 ± 0.01	1.06 ± 0.14
	Auxis thazard	Frigate tuna	FRI	18	38.7 ± 4.2	0.092 ± 0.042	1.55 ± 0.65	0.22 ± 0.09	1.88 ± 0.80
	Euthynnus affinis	Kawakawa	KAW	13	48.1 ± 7.9	0.152 ± 0.068	2.28 ± 1.24	0.37 ± 0.25	2.88 ± 1.66

Table 3. ANOVA results testing the influence of species, fish length and their interactions on total mercury and EPA+DHA contents, and hazard quotient values, obtained for 20 bycatch fish species from the western Indian Ocean in 2018. DHA = docosahexaenoic acid (22:6n-3); EPA = Eicosapentaenoic acid (20:5n-3); df = degrees of freedom; Sum Sq = sum square error; F = Fisher statistic; p = p-value.

Factors	Mercury				EPA+DHA				Hazard Quotient			
	df	Sum Sq	F	p	df	Sum Sq	F	p	df	Sum Sq	F	p
Species	19	167.8	40.5	**<0.001**	19	50.1	32.2	**<0.001**	19	216.8	34.5	**<0.001**
Length	1	23.5	107.7	**<0.001**	1	0.9	11.4	**0.001**	1	15.1	45.6	**<0.001**
Species*Length	19	14.4	3.5	**<0.001**	19	4.2	2.7	**0.001**	19	17.2	2.7	**0.001**
Residuals	135	29.5			135	11.0			135	44.6		

Table 4. Daily serving of fish fillet (g) required to cover eicosapentaenoic + docosahexaenoic acids (EPA+DHA) needs for young children, children, and adults (FAO/WHO, 2008).

English name	Code	Daily serving portion (g)		
		Young children	Children	Adults
Rough triggerfish	CNT	140	234	280
Flat needlefish	BAF	117	196	235
Mackerel scad	MSD	57	94	113
Rainbow runner	RRU	84	140	168
Longfin yellowtail	YTL	154	257	309
Cottonmouth jack	USE	48	80	96
Silky shark	FAL	99	166	199
Pompano dolphinfish	CFW	99	165	198
Common dolphinfish	DOL	105	176	211
Batfishes	BAT	801	1335	1602
Indo-Pacific sailfish	SFA	142	236	283
Great barracuda	GBA	132	220	264
Striped marlin	MLS	84	141	169
Blue sea chub	KYC	102	170	204
Brassy chub	KYV	85	142	171
Tripletail	LOB	147	246	295
Unicorn leatherjacket	ALM	115	191	229
Wahoo	WAH	162	269	323
Frigate tuna	FRI	112	187	225
Kawakawa	KAW	187	311	374

Figure 1. Correlation plot among individuals length, mercury (THg) and nutritional contents (protein, fat, EPA+DHA contents and omega-6/omega-3 ratio) of 20 bycatch fish species collected from the western Indian Ocean in 2018. The coloured cells indicate a significant correlation between the two tracers ($p < 0.05$) while the blank cells indicate a non-significant correlation. The numbers in the cells are the associated Spearman's correlation coefficient (ϱ) calculated for each pair and the cell's colour intensity is proportional to ϱ. DHA = docosahexaenoic acid (22:6n-3), EPA = Eicosapentaenoic acid (20:5n-3).

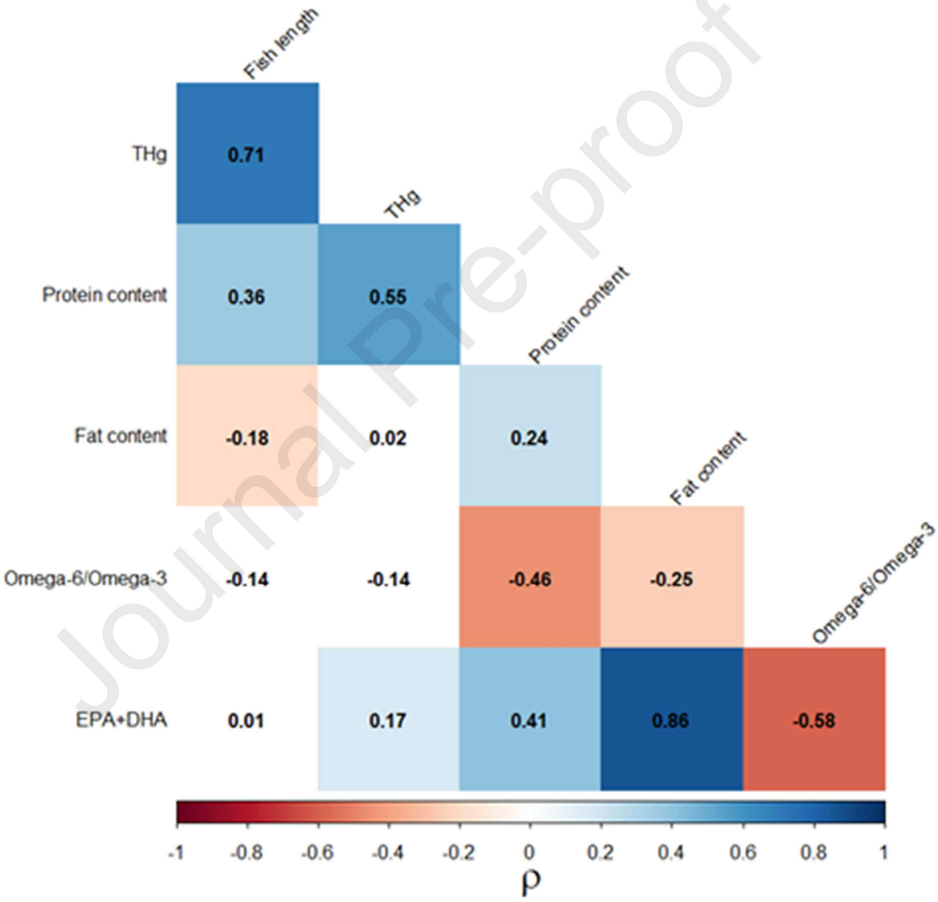


Figure 2. Changes in total mercury levels (THg, ppm ww) and eicosapentaenoic + docosahexaenoic acid contents (EPA+DHA, mg.g^{-1} ww) with fish length (cm) for 20 bycatch fish species collected from the western Indian Ocean in 2018. Linear regressions are plotted when significant ($p < 0.05$). See Table 2 for definition of species acronyms. Y-axis is log scale.

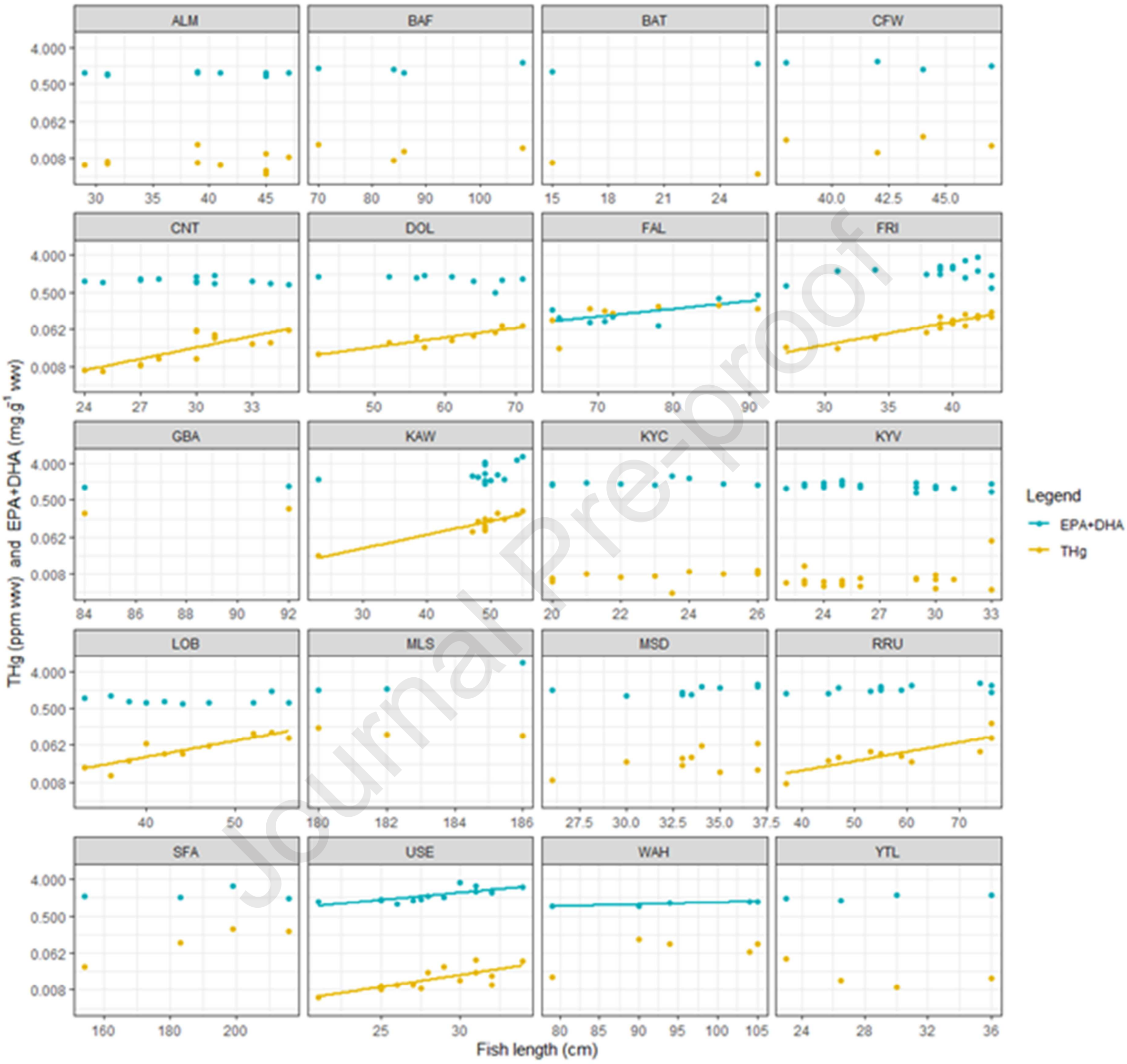


Figure 3. Boxplots of hazard quotient values (HQ) based on total mercury levels and eicosapentaenoic + docosahexaenoic acid (EPA+DHA) contents for 20 bycatch fish species collected from the western Indian Ocean in 2018. HQ were computed for 3 people categories (young children, children and adults; see Table 1 for parameters). The horizontal grey line defines the HQ threshold of 1, and species (X-axis) are ordered according to their mean nutritional rank. See Table 2 for definition of species acronyms and details on nutritional composition. Y-axis is log scale.

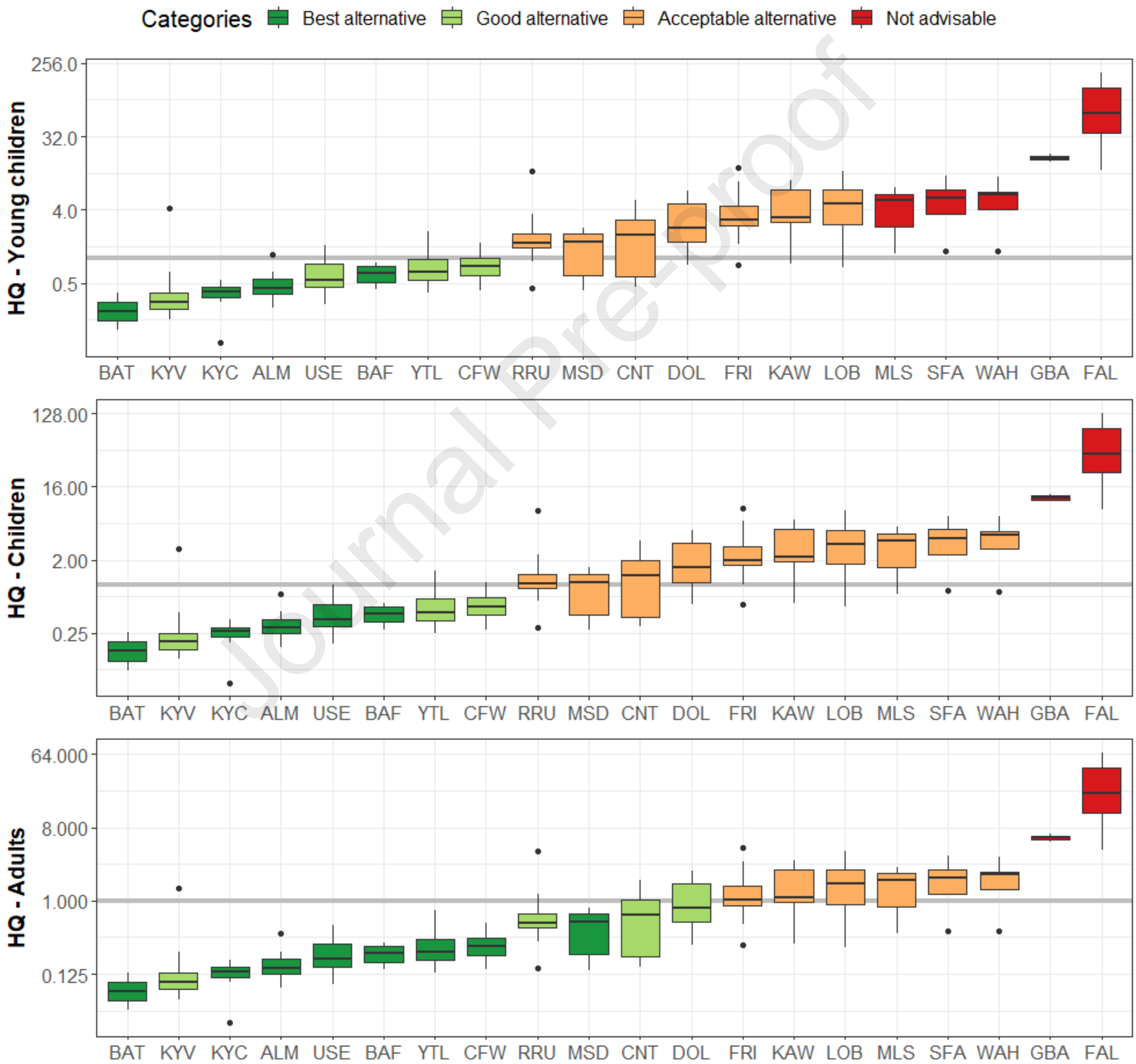
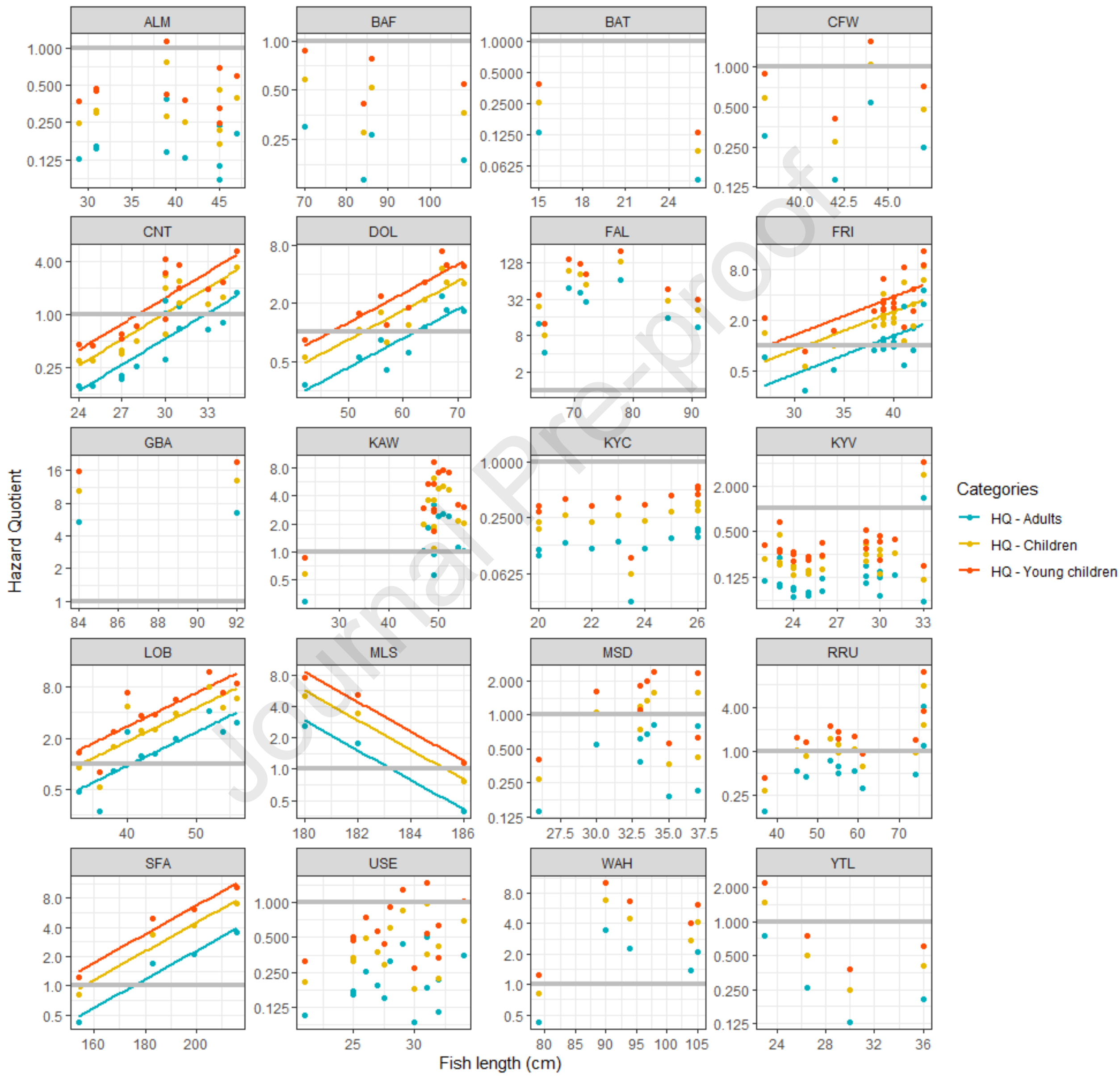


Figure 4. Changes in hazard quotient (HQ) with fish length (cm) for 20 bycatch species collected from the western Indian Ocean in 2018. Scales are adjusted to each species. The horizontal grey line defines the HQ threshold of 1 (HQ < 1 when benefit is greater than risk and vice versa). Linear regressions are plotted when significant ($p < 0.05$). See Table 2 for definition of species acronyms. Y-axis is log scale.



Highlights

- Mercury and omega-3 were quantified in 20 fish species from tuna fisheries bycatch
- All species are good protein sources, with low omega-6/omega-3 ratio
- Eight species are of high interest, especially cottonmouth jack and flat needle fish
- Silky shark and great barracuda are not advised for consumption (low omega-3, high mercury)