Title

Are concentrations of pollutants in sharks, rays and skates (Elasmobranchii) a cause for concern? A systematic review

Authors

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Abstract

This review represents a comprehensive analysis on pollutants in elasmobranchs including meta-analysis on the most studied pollutants: mercury, cadmium, PCBs and DDTs, in muscle and liver tissue. Elasmobranchs are particularly vulnerable to pollutant exposure which may pose a risk to the organism as well as humans that consume elasmobranch products. The highest concentrations of pollutants were found in sharks occupying top trophic levels (Carcharhiniformes and Lamniformes). A human health risk assessment identified that children and adults consuming shark once a week are exposed to over three times more mercury than is recommended by the US EPA. This poses a risk to local fishing communities and international consumers of shark-based products, as well as those subject to the widespread mislabelling of elasmobranch products. Wider screening studies are recommended to determine the risk to elasmobranchs from emerging pollutants and more robust studies are recommended to assess the risks to human health.

Keywords: Elasmobranch; Pollution; Mercury; Cadmium; PCB; DDT.

1. Introduction

Human activities are the main driver behind the rapid loss of the world's biodiversity (Derraik, 2002; Sanderson et al., 2002; McKee et al., 2004). Factors such as pollution, climate change, overexploitation and habitat loss now affect most marine ecosystems on the planet, with human activities causing irreversible damage (Derraik, 2002; Islam and Tanaka, 2004; Dulvy et al., 2014; EEA, 2018). In recent years there has been growing concern for the increasing prevalence of pollutants in the marine environment, their effect on marine organisms, and subsequent effects on humans (Tanabe et al., 1983; Blocksom et al., 2010; Corsolini et al., 2014; Jepson et al., 2016). Persistent organic pollutants (POPs), heavy metals, crude oil and marine debris (e.g. marine litter or microplastics) represent the most common marine pollutants globally (United Nations Environment Program, 2017). Some of these substances are used intentionally as disease and pest control, as well as in manufacturing and industrial processes. These substances can also be produced unintentionally as by-products through industrial processes such as waste incineration, vehicle emissions, and cigarette smoke, as well natural processes such as volcanic activity and forest fires (El-Shahawi et al., 2010; Megson et al., 2013; WHO, 2020). Pollutants can enter the aquatic environment through atmospheric deposition, erosion, urban discharge, combustion and industrial charges (Wang et al., 2004; Morrison and Murphy, 2010; Megson et al., 2013).

Many pollutants bioaccumulate and biomagnify, and thus, apex predators usually have exposure to disproportionately high concentrations of pollutants compared to environmental levels. Pollutants in teleost fish, molluscs and marine mammals have been well-studied (Tanabe et al., 1983; Streit, 1998; Blocksom et al., 2010; Sharma et al., 2014; Jepson et al., 2016; Barone et al., 2018; Desforges et al., 2018), and have been shown to cause adverse health effects including suppressed reproductive development effects, immunosuppression, endocrine disruption and oxidative stress (Letcher et al., 2010). Less attention has been paid to pollutants in elasmobranchs compared to other vertebrate groups, which is especially concerning in light of the high trophic position of elasmobranchs and their continued population decline (Dulvy et al., 2014).

Elasmobranchs belong to the class Chondrichthyans, which are cartilaginous fish that make up one of the oldest and most ecologically diverse vertebrate lineages, arising over 420 million years ago. They occupy the top tiers of aquatic food chains and are present in every ocean. Many elasmobranchs play a crucial role in the top-down control of coastal and oceanic ecosystem structure and function (Ebert et al., 2013; Dulvy et al., 2014). It is estimated that 30% of all Chondrichthyan species are currently threatened with extinction, where 21% of rays and skates, and 17% of sharks are classified as threatened (encompassing IUCN Red List categories 'critically endangered', 'endangered' and 'vulnerable'). In reality, this number is likely to be higher due to the large proportion (n = 438) of species that are listed as 'data deficient' and have not (yet) been assessed (Dulvy et al., 2008, 2014; Gray and Kennelly, 2018; IUCN, 2020). Elasmobranchs exhibit biological and ecological traits similar to those of large-bodied mammals; maturing late, reproducing slowly, having small numbers of offspring (García et al., 2008; Dulvy et al., 2014). The combination of these traits and their high trophic level puts elasmobranchs at relatively higher risk from exposure to pollutants.

All humans are exposed to pollutants throughout their lifetime, with diet being the most significant exposure pathway for many pollutants that bioaccumulate (e.g. lipophilic compounds such as PCBs) (Johansen et al., 2004; Fleming et al., 2006; Sharma et al., 2014).

Twenty seven percent (1.9 billion people) of the world's population lives within 100 km of the coast (Fleming et al., 2006; Kumma et al., 2016). Although variable globally, many of these coastal countries and communities depend on fishing as a source of income, and seafood can make up the majority of their diet (Johansen et al., 2004; Fleming et al., 2006; Zheng et al., 2007; Brunner et al., 2009; Sharma et al., 2014; Bruce-Vanderpuije et al., 2019). Exposure to pollutants such as PCBs, mercury and dioxins, have been linked to cancer, liver and kidney damage, immunosuppression, reproductive defects, and endocrine disruption (Vračko et al., 2007; Zheng et al., 2007; Kim et al., 2013; EFSA et al., 2019). Pregnant women and young children are especially vulnerable to the health risks associated with exposure to these contaminants (Patandin et al., 1999; Bruce-Vanderpuije et al., 2019). Although elasmobranchs may not typically be considered as a primary food source in many non-coastal regions, products deriving from sharks, rays and skates are consumed, and used worldwide (Staffen et al., 2017; Almerón-Souza et al., 2018; Bernardo et al., 2020). Examples of consumption include shark fin soup, the use of traditional Chinese medicine (e.g. gill plates) and the intake of dietary supplements (e.g. liver oil and cartilage supplements). In addition, compounds deriving from elasmobranchs have been found in cosmetic products (Wong et al., 2009; Liu et al., 2013; Dulvy et al., 2014; Fields et al., 2015; Zeng et al., 2016; Cardeñosa et al., 2017; Steinke et al., 2017; Almerón-Souza et al., 2018; Ferretti et al., 2020). Shark meat is also often unintentionally consumed when it is mislabelled (e.g. as other types of elasmobranchs or teleost fish), which means that consumers are unaware that they are consuming shark products (Hobbs et al., 2019; Pazartzi et al., 2019). Shark may be traded under names such as 'white fish', 'corvina', 'toyo', or 'cação', and can end up being consumed in countries where eating sharks is not culturally popular (Bornatowski et al., 2014; Almerón-Souza et al., 2018; Bernardo et al., 2020), as shown in the recent study that found threatened shark species (e.g.

spiny dogfish) being sold at fish and chip shops in the UK (Hobbs et al., 2019). This is especially concerning due to the high concentrations of pollutants found in sharks (Holmes et al., 2009; Barbuto et al., 2010; Filonzi et al., 2010; Gilbert, Baduel, et al., 2015; Gilbert, Reichelt-Brushett, et al., 2015; Alves et al., 2016).

Despite the ecological and economical importance of elasmobranchs, the impact contaminants have on their health is poorly understood, as are the risks to humans through consumption of shark meat. No previous reviews have been carried out for pollutants in all elasmobranchs, the most recent review was performed on rays and skates only (Batoids) (Bezerra et al., 2019). The aim of this manuscript is to address this current knowledge gap by providing a thorough review of pollutant concentrations in all elasmobranchs (but with a specific focus on sharks). Specifically this review aims to 1) identify publication trends for elasmobranch pollution studies, 2) examine the variation in pollution concentrations between taxa, and determine elasmobranch groups most at risk from exposure to marine pollution, 4) relate concentrations of pollutants to toxic thresholds and discuss potential risks of consuming shark meat from a human health perspective, and 5) identify current knowledge gaps and discuss future recommendations.

2. Methods

2.1. Study selection

The present systematic review follows the 2009 PRISMA guidelines (Moher et al., 2009) to identify research articles on marine pollution in elasmobranchs (flowchart, SI 1.1.). Eligibility for inclusion in this review was assessed independently by two reviewers (GPT and DB). Studies were incorporated based on the following inclusion criteria: the study reported on pollutant concentrations in elasmobranchs (though the study did not have to focus primarily on elasmobranchs to be considered for inclusion), the study was published between January 1999 and November 2019, the study was published in a peer-reviewed journal, and the study reported original research. Studies were considered from any country or region and on any contaminant type, as long they were published in English. Information on other taxa (non-elasmobranchs) were not included in this study. 'Grey literature' was not considered in this study as these papers often do not undergo the same peer-review process and are often not available online.

The following search terms were used to identify papers on two separate search engines (Web of Science and Scopus): *"shark*", "ray*", "sawfish*", "skate*", "elasmobranch*", "contaminant*", "contamination", "heavy metal*", "persistent organic pollutant*", "microplastic*", "organochloride", "tissue*", "fin*", "ingest*", "bioaccumulation", "bioaccumulate*"*. The following text "AND not *x-ray"* had to be specified as an exclusion criterion due to the high volume of papers identified in the initial search that were not relevant. Google Scholar was excluded, as it returned a large number of non-relevant papers (over 1000). A number of papers were found based on the studies identified through the above search; for example, three additional papers were added based on the systematic review published on trace metals and POPs in rays and skates (Batoids) (Bezerra et al., 2019).

2.2. Data collection

For every eligible study, general information was collected including author(s), year published, journal, pollutant (e.g. POPs, trace elements, plastic and radionuclides), taxa (species, family, order and superorder), common name, total number of elasmobranchs, area of study, ocean, risk to organism and/or humans and whether the primary focus was on elasmobranchs. The trophic level for all species identified from the scientific literature was sourced from FishBase (Froese and Pauly, 2019). The tissue type analysed was also recorded, specifically whether this concerned liver, fin, kidney, gills, reproductive organs, gastrointestinal system, or other. Reproductive organs included: egg, embryo, gonads, yolk, ovaries and ova; digestive system included: stomach, stomach content, digestive system, intestine and intestinal tract. The current IUCN Red List status (IUCN, 2020) of each species was recorded. Species were also grouped into their superorder Selachimorpha or Batoidea. IUCN status 2020 was categorised as followed; DD = Data Deficient, LC = Least Concern, NT = Near Threatened, VU = Vulnerable, EN =Endangered and CR = Critically Endangered. Pollutants were grouped into five categories: POPs, plastic, trace elements, radionuclides and other (SI 1 and 2).

2.3. Meta-analysis

A meta-analysis was carried out on total mercury (THg), cadmium (Cd), ΣPCB and ΣDDT concentrations in the muscle and liver tissue of elasmobranchs and were recorded on a wet weight basis (dry and lipid weight in SI 1.8. and 2.2.). Muscle and liver tissue were recorded as these were the most commonly reported tissue types, as well as being the most significant in terms of human exposure (through consumption). Data was converted to ng g^{-1} when necessary. Mean values were calculated when more than one individual was reported for one species. Where ranges were reported, a simple average of the upper and lower bounds of the range was calculated. Genders were grouped together, as were different age classes, so the meta-analysis could be focused on evaluating trends in the concentration of pollutants in different elasmobranch groups. Mean concentrations were reported to three significant figures.

2.4. Statistical analysis

Statistical analysis and data visualisation were carried out in R 3.6.1 (R Core Team, 2019). Data was tested for normality with all variables found to be not normally distributed; non-parametric statistical methods were used. A chi-square goodness of fit test was used to examine whether the frequency of studies published across oceans and seas was evenly distributed. Wilcoxon rank-sum tests were used to compare differences in pollutant concentrations between muscle and liver tissue and, also between Selachimorpha and Batoidea. Kruskal-Wallis rank-sum tests and pairwise multiple comparison test ('Kruskalmc') using the "pgirmess" package (Giraudoux, 2018) were used to assess differences in pollutant concentrations across orders for both tissue types.

3. Publication trends

3.1. General information

This review examined a total of 176 studies on pollutants in elasmobranchs that were published between January 1999 and November 2019. Sixty-five percent of these studies were solely focussed on elasmobranchs (n = 115) and 35% included other organisms (e.g. fish and marine mammals) (n = 61). The most-studied tissue types included muscle (68%), liver (47%) and organs within the gastrointestinal tract (17%). Other tissue types included fin (14%), reproductive system (14%), gills (9%), kidney (7%), unknown (1%) and other (10%).

3.2. Overview of pollutants studied

A total of 111 papers focussed on trace elements, 59 on POPs, 12 on plastic, 7 on radionuclides, 3 on cholinesterases (ChEs) and lipid peroxidation (LP), 1 on endocrine-disrupting chemicals, and 1 on synthetic musk fragrances. Sixty three percent (n = 111) of all studies were focussed on trace elements (see SI 2.1. for more details), with 84% (n = 93) of these papers examining mercury (Hg) and 41% (n = 45) examining cadmium (Cd). Studies on POPs made up 32% (n = 57) of the total number of studies, where PCBs (74% of these studies; n = 42) and DDTs (55% of these studies; n = 31) were the most studied POPs. Other POPs included polybrominated diphenyl ethers (PBDEs), polychlorinated dibenzo-p-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs) and dioxin-like PCBs (DL-PCBs), non-dioxin-like PCBs (NDL-PCBs), organochlorine pesticides (e.g. DDT and its metabolites, dieldrin, endrin and chlordane), hexachlorocyclohexane (HCH) and hexachlorobenzene (HBH), chlorobenzene, per- and polyfluoroalkyl substances (PFAS), polycyclic aromatic hydrocarbons (PAHs), and halogenated flame retardants (HFR).

Ninety-two studies (52%) discussed pollutant exposure risk in elasmobranchs, and 96 (55%) discussed the risks to humans. Forty-five studies (26%) discussed both the risks to elasmobranchs and humans, while 33 (19%) studies did not discuss risks to either elasmobranchs or humans.

There was a spike in the number of studies focussing on pollutants in elasmobranchs from 2013 to 2017, especially with regard to trace elements and POPs (figure 1). This could be due to the recent advances in cheaper, faster and more accurate analysis techniques as well as an increase in interest from human health and environmental perspectives (Cole et al., 2011;

Wright et al., 2013; Boucher and Friot, 2017). Plastics, such as microplastics and single-use-plastic, have become a recent important environmental concern and focus for researchers, this is evident from the increase in studies from 2016 onwards (figure 1) (Wright et al., 2013; Ivar Do Sul and Costa, 2014; Gall and Thompson, 2015; Miranda and de Carvalho-Souza, 2016; Alomar and Deudero, 2017; Fossi et al., 2017; Pegado et al., 2018; Smith, 2018). The media and documentaries, such as Blue Planet II (presented by the BBC), have shifted consumers' views, as well as aided in the adoption of new laws on microplastics and single-use-plastic (Barboza and Gimenez, 2015; Xanthos and Walker, 2017; Henderson and Green, 2020). The recent advances in analysis techniques have allowed for a wider scope of studies focussing on emerging pollutants (Nikolaou et al., 2009); in spite of this, most of the studies targeted trace elements, PCBs, and DDTs, which may be because there are more standardised methods to analyse these pollutants in elasmobranchs rather than microplastics, and some of the more emerging and toxic POPs that require lower detection limits (e.g. dioxins, PFAS and halogenated flame retardants).

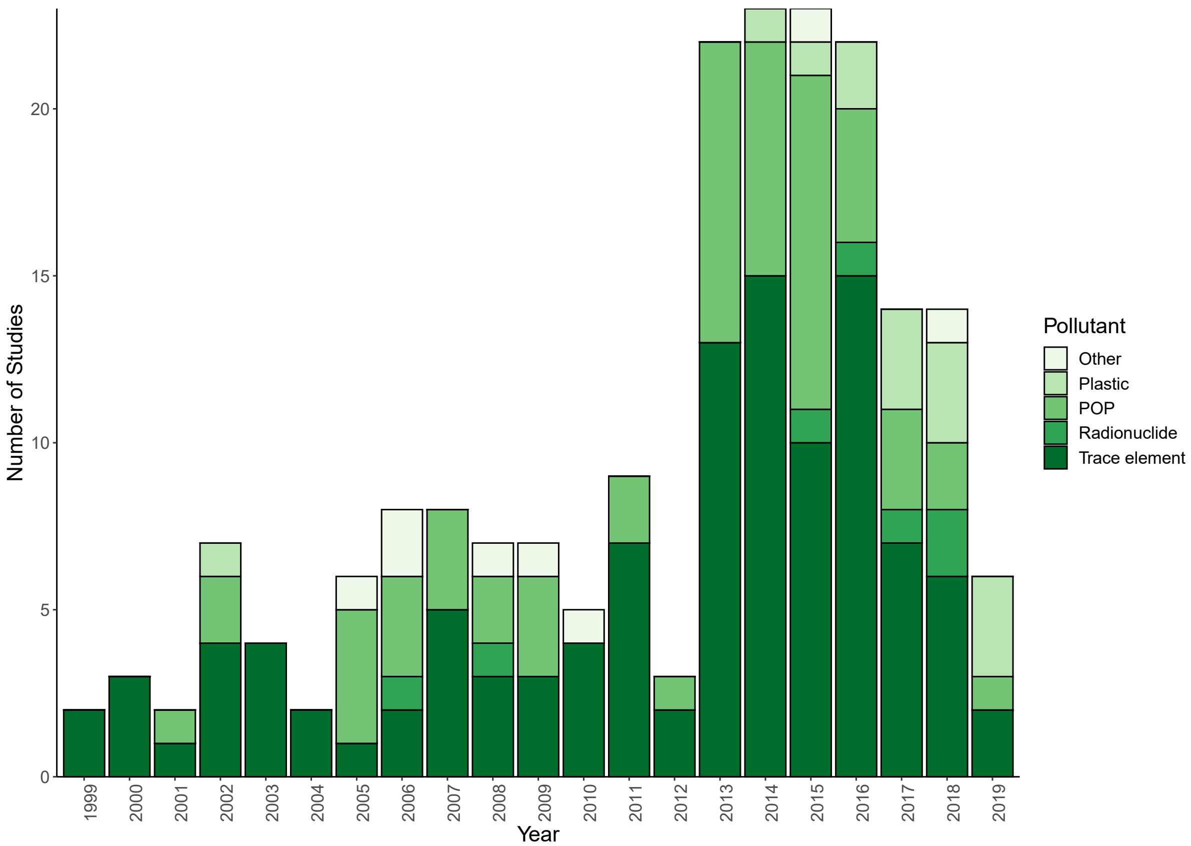

Figure 1. Total number of studies carried out on different pollutant types (Plastic, POP, Radionuclide and Trace Element, Other). Total number of studies (n=176); some studies reported on more than one type of pollutant (January 1999 – November 2019).

The majority of studies were published on trace elements (n = 62) and POPs (n = 31) in Carcharhiniformes, followed by trace elements in Rajiformes (n = 20), Squaliformes (n = 20) and Lamniformes (n = 19) (SI 1.5.). Forty-nine species of rays and skates (Batoidea), and 47 sharks (Selachimorpha) were reported on three times or less. Fifty-five species, 13 families and four orders were recorded for superorder Batoidea. The most represented Batoid species were thornback skates (*Raja clavata*) (8 studies), brown skates (*Raja miraletus*) (5 studies) and starry skates (*Raja asterias*) (5 studies). A total of 80 species, 20 families and six orders were recorded for superorder Selachimorpha. The most reported on shark species were blue sharks (*Prionace glauca*) (28 studies), short fin mako sharks (*Isurus oxyrinchus*) (22 studies) and small spotted catsharks (*Scyliorhinus canicula*) (19 studies). Hence, there appears to be a publication bias towards common and globally occurring species of sharks that are frequently caught in longline fisheries.

3.3. IUCN status

Species reported were categorised into groups based on their IUCN Red List status (IUCN, 2020), and their superorder (Selachimorpha or Batoidea). Three species of sharks were classed as CR, 7 as EN, 17 as VU, 18 as LC, 14 as DD, and 5 species were unknown. For rays and skates, one species was classed as CR, 6 as EN, 9 as VU, 7 as NT, 17 as LC, 13 as DD and 7 species were unknown. No studies reported on species of sawfish from the order Pristiformes despite their endangered and critically endangered IUCN status (IUCN, 2020). Most studies focussed on species that were listed as vulnerable or least concern.

3.4. Geographical distribution

There was relatively good global coverage of studies focussing on elasmobranchs, but the majority were carried out in the North Atlantic Ocean (63 studies), North Pacific Ocean (42 studies) and Mediterranean Sea (36 studies). Lesser studied areas included the South Pacific Ocean (14 studies), Indian Ocean (15 studies) and South Atlantic Ocean (21 studies) (figure 2) (see SI 1.6. for specific sampling locations). Areas in the Southern Hemisphere such as the South Pacific (including Eastern Pacific), South Atlantic and Indian Ocean (including the Red Sea and Persian Gulf) received proportionately less attention despite being global hotspots for elasmobranch occurrence (Lucifora et al., 2011; Dulvy et al., 2014; Gray and Kennelly, 2018; Derrick et al., 2020). With a bias towards certain regions, we may not understand the full extent to which elasmobranchs are exposed to pollutants. This is especially concerning as large-scale commercial fisheries often overlap with these hotspots putting humans at risk from exposure to high concentrations of pollutants if they consume products from these areas (Lucifora et al., 2011; Ferretti et al., 2020). It is crucial that future studies focus on regions that have received less attention in order to accurately identify the global threats to marine organisms as well as the humans that consume these products.

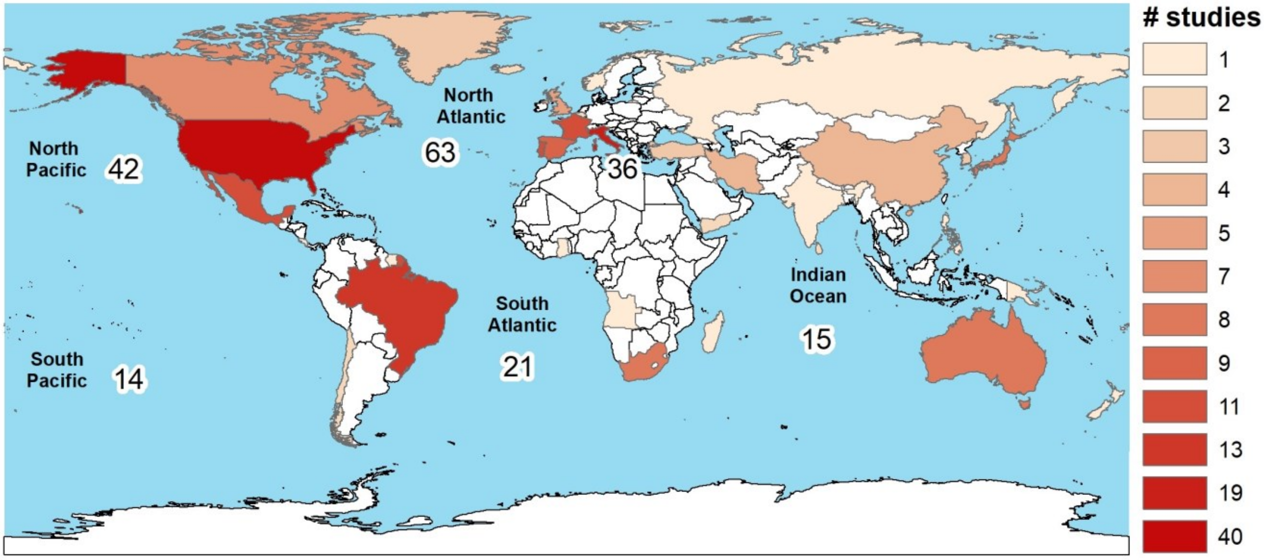

Figure 2. Geographical distribution from studies published on pollutants in elasmobranchs. The numbers represent the number of studies performed for each ocean (North Pacific, South Pacific, North Atlantic, South Atlantic and Indian Ocean), with the coloured shading showing how many studies were conducted by each country. The number of studies were not even across area of study (χ^2 = 56.885, df = 5, $p < 0.001$) where more studies were published in the North Atlantic Ocean than other locations.

4. Concentrations of pollutants in elasmobranchs

A meta-analysis was carried out on the concentrations of THg, Cd, ΣPCBs and ΣDDTs in the muscle and liver tissue of different elasmobranch orders, as these were the most represented pollutants in the literature. A total of 108 from the initial 176 studies were included in the meta-analysis (74 studies on mercury, 35 on cadmium, 41 on ΣPCBs and 28 ΣDDTs) (see SI 1.8.

and SI 2.2. for more information). Within the literature there was variation in how concentrations were reported as either dry weight, lipid weight or wet weight was used. To allow comparisons between pollutants and enable a human health risk assessment, only wet weight (n = 75) is discussed within the body of this review, however all dry weight and lipid weight data is presented in SI 1.8. and 2.2.

4.1.1. Total mercury (THg)

Mercury concentrations were significantly higher in muscle (1430 ± 2330 ng g^{-1}) than in liver tissue (522 ± 971 ng g^{-1}) (Wilcoxon: W = 966, $p < 0.001$). Pairwise comparisons indicated that THg concentrations of muscle tissue in Carcharhiniformes (1520 ± 1900 ng g^{-1}, n = 826) and Lamniformes (2580 ± 4790 ng g^{-1}, n = 195) were significantly higher than concentrations in liver tissue (839 ± 1438 ng g^{-1}, n = 84 and 85.5 ± 53.6 ng g^{-1}, n = 108) (figure 3). THg did not differ between orders in liver tissue (Kruskal – Wallis: χ^2 = 9.79, df = 5, p = 0.081), but did in muscle tissue (Kruskal – Wallis: χ^2 = 25.965, $p < 0.01$). A multiple comparison test on muscle tissue indicated that concentrations of mercury were higher in Carcharhiniformes (1520 ± 1900 ng g^{-1}, n = 1739), Lamniformes (2580 ± 4790 ng g^{-1}, n = 508) and Squaliformes (1610 ± 1040 ng g^{-1}, n = 415) than in Myliobatiformes (383 ± 350 ng g^{-1}, n = 195) (figure 3). Mercury concentrations in liver tissue ranged between 4 ng g^{-1} in giant manta rays (*Mobula birostris*) (n = 6) caught along the coast of Takoradi, Ghana (Essumang, 2009) and 20,800 ng g^{-1} in short fin mako sharks from Southern California, North Pacific (Lyons et al., 2015). Mercury concentrations in muscle tissue ranged between 4 ng g^{-1} in giant manta rays (n = 6) from Takoradi, Ghana (Essumang, 2009) and 4620 ng g^{-1} in smooth tooth black tip sharks (*Carcharhinus leiodon*) (n = 7) from the Arabian Gulf (Moore et al., 2015).

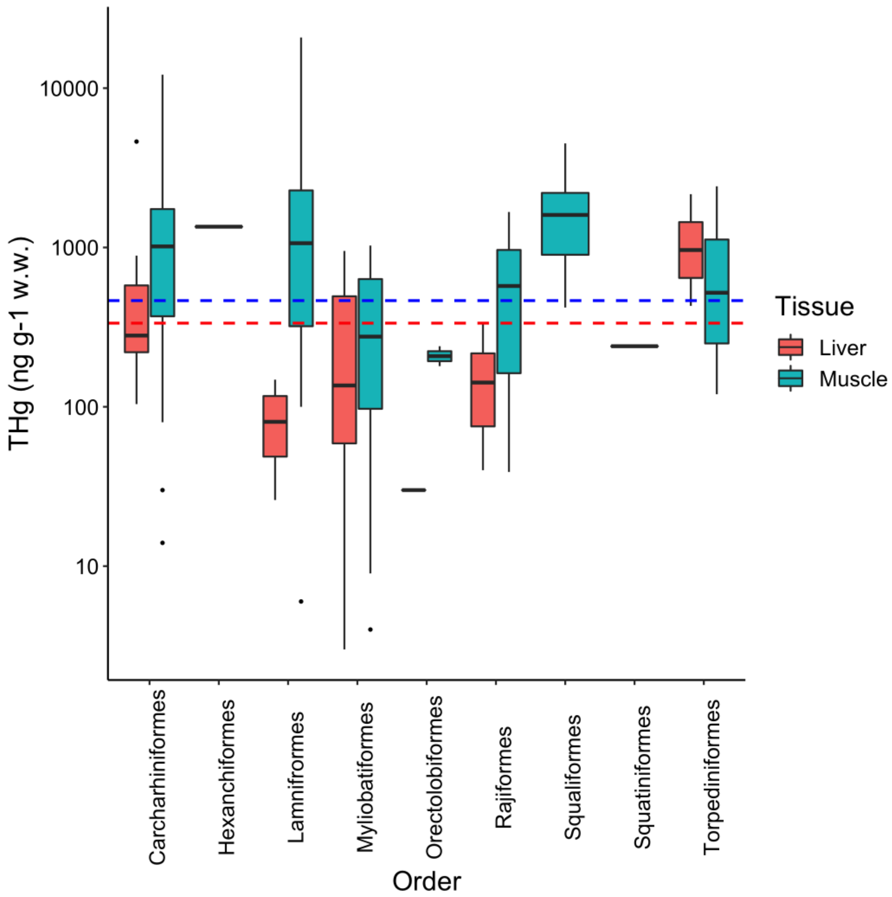

Figure 3. Total mercury (THg) concentrations in the muscle and liver tissue of different elasmobranch groups reported globally. Values are reported in ng g^{-1} on wet weight (w.w.) basis. The tolerable concentration of THg in one serving of fish (113 g) for adults indicated with a blue dashed line, and one serving of 28 g in children (two-years-old) with a red dashed line. The upper limit was set at 464 µg kg^{-1} (ng g^{-1}) per week for adults and the lower limit at 335 µg kg^{-1} (ng g^{-1}) per week in children (EPA, 2020).

4.1.2. Cadmium (Cd)

Cd concentrations were significantly higher in liver tissue (7050 ± 21200 ng g^{-1}) than in muscle tissue (160 ± 397 ng g^{-1}) (Wilcoxon: W = 917, p<0.001). Pairwise comparisons indicated that Carcharhiniformes (7730 ± 15100 ng g^{-1}) and Rajiformes (16300 ± 34200 ng g^{-1}) had significantly higher concentrations of Cd in muscle than liver tissue (451 ± 813 ng g^{-1} and 115 ± 181 ng g^{-1}) (figure 4). Cd concentrations did not differ between orders in muscle tissue

(Kruskal – Wallis: $\chi^2 = 6.802$, df = 6, p = 0.339) but did in liver tissue (Kruskal – Wallis: $\chi^2 = 12.51$, df = 5, $p < 0.05$). A multiple comparison test indicated that Carcharhiniformes (7730 ± 15100 ng g^{-1}, n = 84) had significantly higher concentrations of Cd in their liver than Torpediniformes (45 ± 19 ng g^{-1}, n = 155) (figure 4). The lowest concentrations of Cd in muscle tissue of 10 ng g^{-1} were observed in sandy (*Leucoraja circularis*) (n = 20) and shagreen skates (*Leucoraja fullonica*) (n = 24) from Bay of Biscay and the Celtic Sea (Nicolaus et al., 2017), blue sharks (n = 20) from southwest waters of Portugal, North East Atlantic (Alves et al., 2016), and whitespotted bamboo sharks (*Chiloscyllium plagiosum*) (n=26) from the southern waters of Hong Kong (Cornish et al., 2007). The highest Cd concentrations in muscle tissue of 2000 ng g^{-1} were observed in small tail sharks (*Carcharhinus porosus*) (n = 12) from Atlantic waters surrounding Trinidad and Tobago (Mohammed and Mohammed, 2017). Cd in the liver ranged between 17 ng g^{-1} in giant manta rays (n = 6) from Takoradi, Ghana (Essumang, 2009) and 87,200 ng g^{-1} lesser guitarfish (*Acroteriobatus annulatus*) (n = 19) from False Bay and Saldanha Bay, South Africa (Morris et al., 2016).

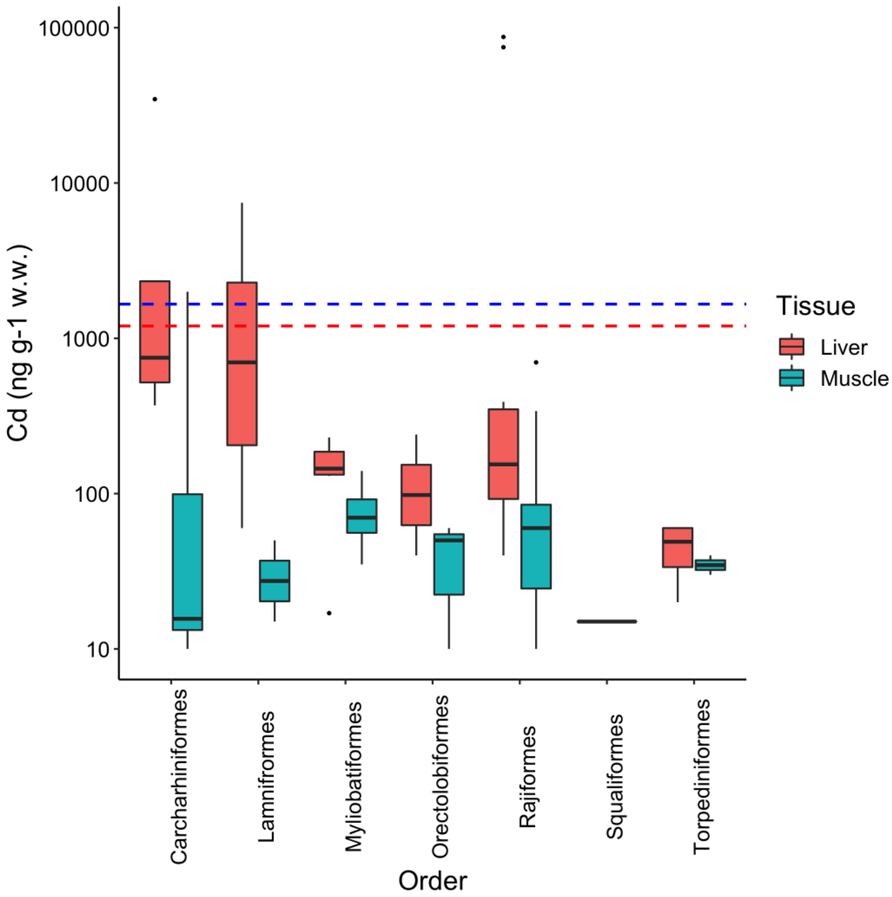

Figure 4. Cadmium (Cd) concentrations in the muscle and liver tissue of different elasmobranch groups reported globally. Values are reported in ng g^{-1} on a wet weight (w.w.) basis. The maximum concentration of Cd in one serving (113 g) of fish for adults is indicated with a blue dashed line, and one serving of 28 g in children (two-years-old) with a red dashed line. The upper limit was set at 1660 µg kg^{-1} (ng g^{-1}) per week for adults and the lower limit at 1200 µg kg^{-1} (ng g^{-1}) per week in children (FAO and WHO, 2013; EFSA, 2016).

4.1.3. Polychlorinated biphenyls (PCBs)

ΣPCB concentrations were significantly greater in liver tissue (6380 ± 9720 ng g^{-1}) than in muscle tissue (14 ± 14 ng g^{-1}) (Wilcoxon: W = 125, $p < 0.001$), though a pairwise comparison did not indicate any significant differences within orders. No significant difference was observed in ΣPCB concentrations between each order in muscle (Kruskal – Wallis: χ^2 = 5.42, df = 3, p = 0.143) and liver tissue (Kruskal – Wallis: χ^2 = 6.959, df = 3, p = 0.073) (figure 5). Concentrations of ΣPCBs in muscle tissue ranged from 1 ng g^{-1} in barndoor skates (*Dipturus laevis*) (n = 13) from Cape Cod, Massachusetts, USA (Lyons and Adams, 2017) to 44.5 ng g^{-1} in Greenland sharks (n = 3) from North East Greenland waters (Corsolini et al., 2014). ΣPCBs in liver tissue ranged from 35.6 ng g^{-1} in Greenland sharks (n = 43) from the Kongsfjorden area, Svalbard, Norway (Molde et al., 2013) to 30,000 ng g^{-1} in one short fin mako shark from Huntington Beach, California, USA (Lyons et al., 2015). Although the total PCB concentration of elasmobranch orders are reported here, these values should be taken tentatively. Due to the different approaches of each study (i.e. taking a subset of PCBs or excluding DL-PCBs), it makes comparing PCB concentrations across orders and the two tissues types challenging. This is an inherent issue when comparing PCB data sets as researches use different analytical techniques and report "total PCBs" in different ways (Megson et al., 2019). Therefore, these values should only be used as a conservative guideline to indicate the potential health risks to elasmobranchs as well as humans consuming products deriving from elasmobranchs.

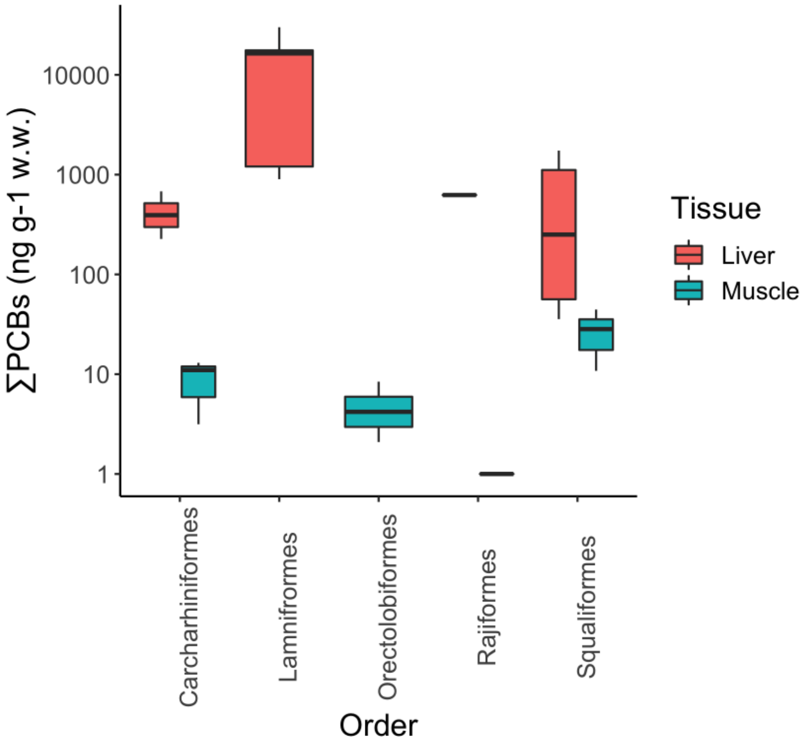

Figure 5. ΣPCB concentrations in the muscle and liver tissue of different elasmobranch groups reported globally. Values are reported in ng g^{-1} on a wet weight (w.w.) basis. No tolerable limit was considered against this data due to inconsistencies in reporting PCB concentrations in the literature.

4.1.4. Dichlorodiphenyltrichloroethane (DDT)

ΣDDT concentrations were significantly greater in liver tissue (19500 ± 37100 ng g^{-1}) than in muscle tissue (10 ± 14 ng g^{-1}) (W = 145, $p < 0.001$). A pairwise comparison of muscle and liver tissue did not indicate any significant differences within each order (figure 6). No significant differences were observed between orders for muscle (Kruskal – Wallis: χ^2 = 3.99, df = 4, p = 0.408) and liver tissue (Kruskal – Wallis: χ^2 = 4.08, df = 3, p = 0.253) (figure 6). Concentrations in muscle tissue ranged from 0.28 ng g^{-1} in barndoor skates (n = 1) collected in offshore waters adjacent to Cape Cod, Massachusetts, USA (Lyons and Adams, 2017) to 49.3 ng g^{-1} in gulper sharks (*Centrophorus granulosus*) (n = 25) from the Mediterranean Sea (Storelli and Marcotrigiano, 2001). Concentrations in the liver ranged from 0.537 ng g^{-1} in Greenland sharks (n = 3) (Corsolini et al., 2014) from North East Greenland to 103,000 ng g^{-1} in great white sharks (n = 30) from North Pacific waters surrounding California, USA (Lyons et al., 2013).

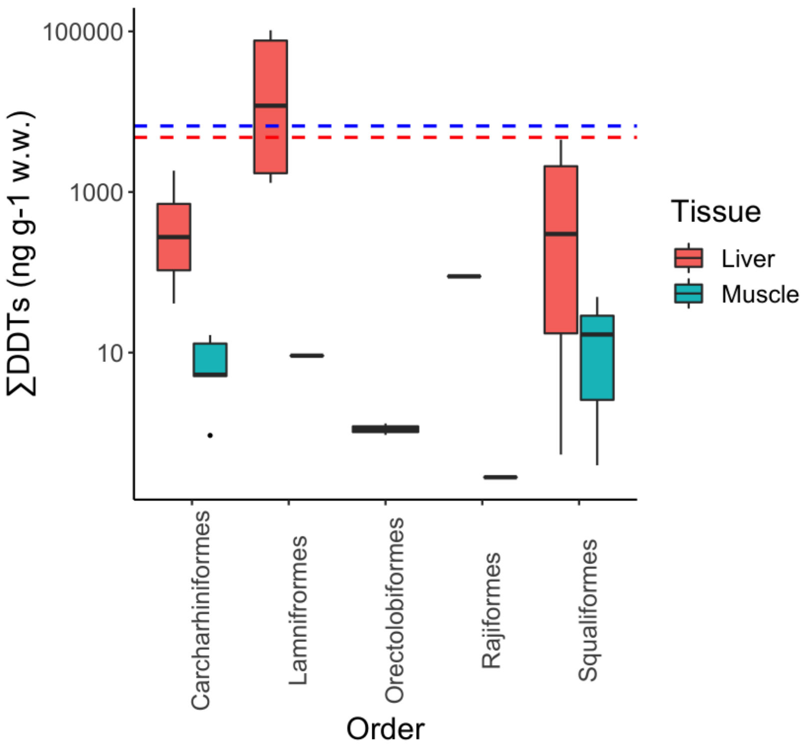

Figure 6. ΣDDT concentrations in the muscle and liver tissue of different elasmobranch groups reported globally. Values are reported in ng g^{-1} on a wet weight (w.w.) basis. The maximum concentration of DDT in one serving (113 g) of fish for adults is indicated with a blue dashed line, and one serving of 28 g in children (two-years-old) with a red dashed line. The upper limit was set at 6.64 mg kg^{-1} (6640 ng g^{-1}) per week for adults and the lower limit at 4.79 mg kg^{-1} (4790 ng g^{-1}) per week in children (WHO, 1961; WHO and FAO, 2000).

4.2. Risk to elasmobranchs

Elasmobranchs are exposed to high concentrations of pollutants throughout their lifetime. Sharks had higher concentrations of pollutants than rays and skates (table 1), with the exception of Cd in bluntnose guitarfish (*Acroteriobatus blochii*) and lesser spotted guitarfish

(*Acroteriobatus annulatus*) belonging to the order Rajiformes. Species belonging to the orders Carcharhiniformes and Lamniformes had the highest concentration of all four pollutants (figure 3 to 6). The variation observed between groups can be explained by the diversity of elasmobranchs, as well as their different habitats, size, age, trophic position, life strategies and diet (Pethybridge et al., 2010; Olin et al., 2014; Beaudry et al., 2015; Sandoval-Herrera et al., 2016; Matulik et al., 2017; McKinney et al., 2017; Morris et al., 2016). Many shark species are migratory predators that feed continuously and as pollutants can vary across geographic regions, species may be exposed to pollutants in different ways (Teffer et al., 2014). Trophic level data revealed that there was a significant positive correlation between THg concentration and trophic level in muscle tissue for sharks, rays and skates (SI 1.10.). A positive trend was observed between trophic level and concentration of PCBs and DDTs in both tissue types, and THg in liver tissue, however, these trends were not statistically significant which could be as a result of the limited data available. Interestingly Cd concentrations seemed to decrease as trophic level increased (SI 1.10.); this anomaly seemed to be primarily driven by high concentrations observed in three elasmobranch species (bluntnose and lesser spotted guitarfish, and megamouth shark).

Previous studies have found that sharks, rays and skates accumulate organic (e.g. PCBs, DDTs and organochlorines) and inorganic (e.g. trace elements) pollutants (Olin et al., 2014; Beaudry et al., 2015; Gilbert et al., 2015; Weijs et al., 2015; Cagnazzi et al., 2019). Elasmobranchs occupying high trophic positions also tend to be long-lived and large-sized, mature late, and have relatively few offspring, which allows for the bioaccumulation of pollutants (Fisk et al., 2002; Cagnazzi et al., 2019; Matulik et al., 2017; McKinney et al., 2016). As well as bioaccumulation, trophic level analysis (SI 1.10.) revealed strong evidence of biomagnification of organic and inorganic pollutants through the food chain. The lowest concentrations of pollutants were observed in rays and skates, especially THg and Cd in giant manta rays. Giant manta rays are secondary consumers that predominantly feed on zooplankton (e.g. krill, shrimp and crabs), which means they may not accumulate pollutants at the same rate as some of the other rays and skates that feed on larger prey (Essumang, 2009; Bezerra et al. 2019; Burgess et al., 2016). Further discussion on pollutant accumulation and risks to Batoids can be found in Bezerra et al. (2019).

There are currently no toxic thresholds for tolerable concentrations of pollutants in elasmobranchs. Studies have suggested that pollutants, such as Hg and Cd, can alter the reproductive physiology of sharks, rays and skates (Molde et al., 2013; Mull et al., 2013; Bendall et al., 2014; Rumbold et al., 2014; Terrazas-López et al., 2016; Bezerra et al., 2019). Elasmobranchs have also been shown to maternally offload a wide range of pollutants to their offspring (Bezerra et al. 2019; Olin et al., 2014; Gilbert, Baduel, et al., 2015; Lyons and Lowe, 2015; Weijs et al., 2015; van Hees and Ebert, 2017). This poses a significant health risk to developing embryos and shark pups as they start their life with higher concentrations of pollutants and will continue to bioaccumulate these contaminants throughout their lifetime (De Boeck et al., 2010; Mull et al., 2013; Olin et al., 2014; Frías-espericueta et al., 2015; Lyons and Adams, 2015; McKinney et al., 2016). One recent study indicated that white sharks (*Carcharodon carcharias*) did not exhibit physiological responses (i.e. no change in enzymatic conditions and leukocyte counts) that would usually be expected when organisms are exposed to high concentrations of heavy metals (Merly et al., 2019). This suggests that some species may be more tolerant to pollutant exposure or are able to biotransform and eliminate organic pollutants (e.g. DDTs and PCBs) more effectively than other species (Corsolini et al., 2014). More studies are needed to assess the risks of pollutants in elasmobranchs to accurately identify any adverse health effects and improve our understanding of the fate and transport of pollutants inside these organisms.

Due to the absence of toxic threshold of ΣPCBs in sharks, concentrations in this study were compared to the “applied” toxic threshold of ΣPCBs in marine mammals as set by Jepson et al. of at lowest 9 mg kg^{-1} and at highest 41 mg kg^{-1} (lipid weight) (Helle et al., 1976; Jepson et al., 2016). Short fin mako sharks and bull sharks exceed the lowest toxicity threshold, with concentrations in their muscle and liver tissue exceeding 37 mg kg^{-1} lipid weight. Studies carried out on marine mammals and teleost fish have found an association between exposure to pollutants and neurological disorders, structural damage to organs and gills, reduced fertility, reproductive developmental effects, oxidative stress, and cancer (Tanabe et al., 1983; Evans, 1987; Blocksom et al., 2010; Pandey, Govind and Madhuri, 2014; Sharma et al., 2014; Jepson et al., 2016; Desforges et al., 2018; Cagnazzi et al., 2019). More research is needed to confirm if elasmobranchs exhibit the same physiological effects that have been established in marine mammals and teleost fish.

More attention has been paid to the risks towards humans who consume shark meat rather than how pollutants affect the organisms themselves. The large amount of resources, funding, time, and planning required, as well as the shy and migratory behaviour of some species, make sampling for elasmobranchs incredibly difficult. This may also explain the opportunistic nature of some studies. The negative portrayal of sharks in the media and in movies such as ‘Jaws’, ‘The Shallows’, ‘Sharknado’ (series of films) and ‘The Meg’ has made gathering support for their conservation extremely difficult (Reynolds et al., 2005;

Simpfendorfer et al., 2011; Friedrich et al., 2014). Seeking funding to carry out pollutant monitoring programs for elasmobranchs is challenging and funding may support projects on species that are often associated with a positive public perception such as marine mammals, sea birds and turtles, rather than sharks, rays and skates.

Determining the exposure risk in elasmobranchs is difficult as there are differences among taxonomic groups, but also among orders, families and species. The high concentrations found in this study suggest that elasmobranchs could be negatively impacted, though to date research on the health impacts of pollutant exposure in elasmobranchs has typically been less extensive than in humans. Establishing baseline thresholds for pollutants in elasmobranchs poses a significant challenge; nevertheless, they currently represent one of the most vulnerable and at-risk taxa (Dulvy et al., 2014; IUCN, 2020) and therefore there is an urgent need to fully understand their susceptibility to pollutant exposure. The urgency is further underlined by the current rapid loss of species, which is driven by existing threats including overfishing, habitat loss, and climate change.

Table 1. Mean ± SD THg, Cd, ΣPCB and ΣDDT concentrations in the muscle and liver tissue of superorder Selachimorpha and Batoidea expressed in ng g^{-1} on a wet weight basis.

Pollutant	Basis	Tissue	Selachimorpha	Batoidea	Sig
THg	Wet Weight	Muscle	1670 ± 2580	598 ± 546	***
		Liver	538 ± 1150	498 ± 666	NS
Cd	Wet Weight	Muscle	272 ± 634	97 ± 142	*
		Liver	4710 ± 10800	8220 ± 25000	*
ΣPCBs	Wet Weight	Muscle	15 ± 14	1	NS
		Liver	6820 ± 9970	625	NS
ΣDDTs	Wet Weight	Muscle	11 ± 14	0.28	NS
		Liver	2140 ± 38100	89	NS

Significant differences in pollutant concentrations between Selachimorpha and Batoidea were indicated at * <0.05, ** <0.01, *** <0.001. NS = p > 0.05.

5. Human health risks

5.1. Human consumption

The consumption of shark is probably best recognised through the shark fin trade (e.g. shark fin soup), though other important exposure pathways are through the use of traditional Chinese medicine (e.g. gill plates), intake of dietary supplements (e.g. liver oil and cartilage supplements) and use of cosmetic products (Wong et al., 2009; Liu et al., 2013; Dulvy et al., 2014; Fields et al., 2015; Zeng et al., 2016; Cardeñosa et al., 2017; Steinke et al., 2017; Almerón-Souza et al., 2018; Ferretti et al., 2020). Cases of mislabelling and species substitution are becoming increasingly prevalent, with evidence also showing an increased occurrence of mislabelling in ray and skate species (Barbuto et al., 2010; Filonzi et al., 2010; Bornatowski et al., 2014; Dulvy et al., 2014; Zeng et al., 2016; Staffen et al., 2017; Almerón-

Souza et al., 2018; Wainwright et al., 2018; Hellberg et al., 2019; Hobbs et al., 2019; Pazartzi et al., 2019). This could be due to the advances in genetic tools for species identification (Barcaccia et al., 2016), but also the monetary incentives from selling shark, ray or skate meat as more highly-valued and expensive species (e.g. tuna, swordfish, mackerel and bonito), as elasmobranchs often represent lower market values and are caught as by-catch (Filonzi et al., 2010). The decrease in landings for commercial bony fish may also put a strain on commercial fisheries (Mullon et al., 2005; Pinsky et al., 2011), resulting in an increase in fraudulent sales of other fish, such as sharks, rays and skates.

Food fraud and product mislabelling have occurred throughout history (Spink and Moyer, 2011; Johnson, 2014): a well-known case is the 'horse meat scandal' (2013), where horse meat was sold as beef (Walker et al., 2013). Food mislabelling is of great concern to the safety of consumers as they may be exposed to allergens (or in the case of sharks, high concentrations of pollutants), without their knowledge. Recent studies have found shark meat in countries where shark is not known to be a primary fish source. Examples of mislabelling include the UK where shark was sold as cod in fish and chip shops (Hobbs et al., 2019) and substitution of threatened sharks (CITES) as non-threatened species in Brazil, Greece, and the USA, amongst others (Bornatowski et al., 2014; Almerón-Souza et al., 2018; Hellberg et al., 2019; Pazartzi et al., 2019; Bernardo et al., 2020). Mislabelling and substitution thus represents not only a threat to vulnerable species of sharks, but also to the consumers of sharks and shark-based products.

5.2. *Hazard quotients*

Hazard quotients were calculated based on the recommended weekly and monthly intake (where applicable) for THg, Cd and ΣDDTs (table 2). The minimum and maximum consumption limits were based on the most vulnerable and most-at-risk individuals; females and children. The adult weight was based on a woman of 75 kg, and the children's weight based on a two-year-old female of 13.4 kg and 11-year-old female of 47.5 kg (see SI 1.9. for more details). The average serving size of 113 g (four ounces) of fish was based on the US EPA's advice for adults and children (aged 11); for children aged two the average serving size was 28 g (EPA, 2020). People consume fish between one to three times per week, though young children on average consume only one serving per week (U.S. Environmental Protection Agency, 2011; EPA, 2020). Exposure risk was calculated using the average pollutant concentrations in the muscle tissue of sharks, as this was considered to be the most likely tissue type to be consumed (see SI 1.9. for more information).

Table 2. Hazard quotients were calculated for Cd, THg and ΣDDT indicating the minimum and maximum risk humans would have from consuming shark meat one to three times per week.

	Hazard Quotient		
	Hg	Cd	ΣDDT
Adult (Female aged 20 yrs or over eating 3x per week)	10.8	0.5	0.00071
Adult (Female aged 20 yrs or over eating 1x per week)	3.6	0.164	0.000236
Child (11 yr old female eating 3x per week)	17	0.776	0.00112
Child (11 yr old female eating 1x per week)	5.69	0.258	0.000373
Child (2 yr old female eating 3x per week)	15	0.68	0.00099
Child (2 yr old female eating 1x per week)	5	0.228	0.000329

5.2.1.Mercury (Hg)

Mercury can be present in the environment in several different forms (organic, inorganic and elemental); within the literature the majority of studies reported on THg and many did not report separately on methylmercury (MeHg) as it makes up 70-100% of total mercury in elasmobranchs (Storelli et al., 2003; Krystek and Ritsema, 2005; Pethybridge et al., 2010; de Carvalho et al., 2014; Rumbold et al., 2014; Alves et al., 2016; Torres et al., 2016; Mohammed and Mohammed, 2017; Chouvelon et al., 2018). The provisional tolerable weekly intake (PTWI) for humans was based on MeHg and was used to calculate the safe consumption limit of mercury in shark muscle tissue for adults and children (FAO and WHO, 2011; EPA, 2020) (table 2). There is currently no scientific consensus on the PTWI of MeHg: the EFSA and WHO recommend a higher PTWI of 1.3 and 1.6 ng g^{-1} of body weight (bw) $week^{-1}$ respectively, whilst US EPA recommends a more conservative PTWI of 0.7 ng g^{-1} of bw $week^{-1}$ (FAO and WHO, 2011; EFSA, 2012; EPA, 2020). Hazard quotients were derived based on the US EPA's PTWI given the human health implications of over consumption of mercury (table 2). Hazard quotients were calculated using the mean concentration of Hg in shark muscle tissue was 1670 ng g^{-1} on a wet weight basis (table 2).

5.2.2. Cadmium

The European Food Safety Authority (EFSA), World Health Organisation (WHO) and the Food and Agricultural Organisation (FAO) set PTWI of Cd from food at 2.5 ng g^{-1} of bw $week^{-1}$ for all age groups (FAO and WHO, 2013; EFSA, 2016).The mean Cd level in shark muscle tissue was 272 ng g^{-1} on a wet weight basis. This value was used to determine hazard quotas for adults and children aged between two and 11 years old (table 2). Although there is less risk of consuming shark muscle meat, Cd concentrations in the liver were much higher (maximum 4710 ng g^{-1}) and therefore shark products should be consumed with caution as Cd is especially toxic to kidneys, accumulating over time leading to renal dysfunction (figure 5) (EFSA, 2016).

5.2.3. DDTs

The provisional tolerable daily intake (PTDI) of ΣDDT as set by the FAO and WHO is 10 ng g^{-1} of bw (70 ng g^{-1} of bw $week^{-1}$) (WHO, 1961) which was confirmed at the Joint Meeting of Pesticide Residues (JMPR) (FAO and WHO) in 2001 (WHO and FAO, 2000). The mean concentration of ΣDDT in shark muscle tissue was 11 ng g^{-1}. Maximum and minimum hazard quotients for children (aged two and 11 years old) and adults were less than 0.01, which indicated that there is a limited risk from exposure to DDT in shark meat when consumed one to three times per week (table 2). Similarly to Cd, concentrations of ΣDDT were higher in the liver of sharks, especially in Lamniformes (41,000 ng g^{-1}), and therefore shark products should be consumed with caution (figure 6).

5.2.4. PCBs

It's challenging to accurately identify the risks to human health posed by PCBs based on the available data in the literature. The health risks from PCBs are calculated using the 12 DL-PCB and PCDD/Fs (FAO and WHO, 1991; van den Berg et al., 1998, 2006; WHO, 2010; Megson et al., 2019) however only three studies out of the 41 on PCBs reported concentrations of all 12 DL-PCBs, with the rest of the data being based on a subset of PCBs (e.g. i7 PCBs) or a "total" PCB concentration (ΣPCB) calculated using anywhere between seven to 55 PCBs (SI 3.1.). This is possibly because the aim of many of these studies was to undertake a baseline screening assessment rather than undertake a detailed human and animal health risk assessment. Studies that reported on the 12 DL-PCBs observed high concentrations (wet weight basis) in the liver (43 ± 6 pg g^{-1}) and muscle tissue (36 ± 6 pg g^{-1}) of Greenland sharks (Corsolini et al., 2014), and in the liver (45972 ± 43967 pg g^{-1}) and muscle tissue (103 ± 77 pg g^{-1}) of blue sharks (Alves et al., 2016) (SI 3). Corsolini et al. (2014) reported a WHO_{2005} toxic equivalence (TEQ) of 5.23 pg TEQ g^{-1} in the muscle tissue of Greenland sharks and Alves et al. (2016) 0.0140 pg TEQ g^{-1} (wet weight) in the muscle tissue of blue sharks (van den Berg et al., 2006). Due to the limited of the data available, only a preliminary human risk assessment could be undertaken. Hazard quotients were calculated based on the EFSA's conservative TWI of 2 pg TEQ kg^{-1} of bw $week^{-1}$ (EFSA et al., 2019). This indicated that adults and children would be exposed to over three times more dioxins and DL-PCBs when consuming muscle tissue from Greenland sharks (Adult HQ = 3.9x, Child aged 11 HQ = 6.2x and Child aged two HQ = 5.5x). Although the total DL-PCB concentration was greater in muscle tissue from blue sharks, when this was converted to a TEQ risk assessment, it indicated that there was a lower risk (HQ = 0.1) from consuming blue shark meat. As POPs are more lipophilic, dioxins and DL-PCBs accumulate in higher concentrations in the liver than in muscle tissue, therefore there may be a significant risk from consuming products derived from the liver that should be investigated (e.g. liver oil capsules, and skin care products that are put directly onto skin). In addition, PCBs are just a subset of dioxin-like-compounds (DLCs) which exhibit the same toxic mode of action. Therefore, to properly assess health risks future studies should also consider determining concentrations of other dioxins and DLCs such as polychlorinated naphthalene (PCNs), polybrominated dibenzo-p-dioxins and dibenzofurans (PBDD/Fs) and mixed halogenated dioxins/furans (PxDD/Fs). This assessment indicated that there may be a significant risk to a human health from consuming DLCs in shark meat. However, more studies that focus on determining DLCs in sharks and shark-based products are needed to accurately assess the human health risks.

5.3. Human health recommendations

The data gathered from this review indicated that humans should avoid consuming shark meat (specifically muscle tissue) as they would be exposed to high levels of mercury. Although there were no observed risks from Cd or DDT in muscle tissue, the higher concentrations in the liver suggest that shark products should be consumed with caution. One serving of shark meat (113 g for adults and 11-year-olds; 28 g for 2-year-olds) would expose adults and children to over three times the maximum recommended mercury consumption limit, and could lead to them experiencing toxic effects (table 2) (Mohammed and Mohammed, 2017; EPA, 2020). Similar findings were observed by the US EPA and in numerous other studies reporting on mercury in sharks (Gomes Ferreira et al., 2004; Burger and Gochfeld, 2011; Escobar-Sánchez et al., 2011; Lopez et al., 2013; Lyons et al., 2013; Olmedo et al., 2013; Vélez-Alavez et al., 2013; Man et al., 2014; Nalluri et al., 2014; Teffer et al., 2014; Corsolini et al., 2014; de Carvalho et al., 2014; Gilbert, Reichelt-Brushett, et al., 2015; Kiszka et al., 2015; Alves et al., 2016; Biton-Porsmoguer et al., 2018; Cagnazzi et al., 2019). Although the US EPA's recommendations of avoiding shark meat are in line with this study, our data indicates that their current limit of 980 ng g^{-1} may be underestimating the risk as average mercury concentrations in sharks exceed this value by 66% (1670 ng g^{-1}).

It should also be noted that this value was an average for all sharks. People consuming sharks from the orders Carcharhiniformes and Lamniformes would be at greater risk as the average mercury concentration in these species exceeded 4000 ng g^{-1}. This is concerning as species belonging to these elasmobranch orders have the highest economic value and so are one of the most targeted group of sharks in the international fin and meat trade. Species include blue sharks (28 studies), silky sharks (*Carcharhinus falciformis*) (6 studies), dusky sharks (*Carcharhinus obscurus*) (9 studies), sandbar sharks (*Carcharhinus plumbeus*) (6 studies), tiger sharks (*Galeocerdo cuvier*) (6 studies), hammerheads (*Sphyrna* spp.), bull sharks (*Carcharhinus leucas*) (14 studies), short fin mako sharks (22 studies), thresher sharks (*Alopias* spp.) (12 studies), and oceanic white tips (*Carcharhinus longimanus*) (5 studies) (Clarke et al., 2006; Worm et al., 2013; Gray and Kennelly, 2018; Ferretti et al., 2020).

The concentrations of mercury in sharks are greater than other regularly-consumed fish species, such as marlin (490 ng g^{-1}), king mackerel (730 ng g^{-1}), swordfish (1000 ng g^{-1}), and bigeye tuna (690 ng g^{-1}) (EPA, 2020). There is evidence that humans that live in coastal areas, especially those who work in the fishing industry, eat twice as much fish as the general population; these groups are therefore likely to be at a greater risk than the general population (Svensson et al., 1995; Leng et al., 2009). Limited biomonitoring studies on these groups have revealed elevated concentrations of POPs (e.g. PCBs and PCDD/Fs) and trace elements (e.g. methylmercury) in their blood and semen (Svensson et al., 1995; Chien et al., 2002; Kiviranta et al., 2002; Toft et al., 2006; Rignell-Hydbom et al., 2007; Cheng et al., 2009). As these individuals are most at risk of pollutant exposure, it is crucial that they are aware of these threats. Any programs that are put into place to outline the health risks to consumers should acknowledge the importance of elasmobranchs for their livelihood and work to provide alternatives for communities that depend on fishing.

Although the focus of this study has been on the consumption of shark muscle tissue, it is important to acknowledge a potential exposure pathway from products deriving from shark liver, including shark liver oil, as well as a potential risk from consuming products deriving from rays and skates (Bezerra et al., 2019). The elevated concentrations of Cd, DDT and PCBs within the liver of sharks suggest that, if anything, risks to human health are exacerbated when shark liver rather than shark muscle is considered. In some cases, for example for PCBs and DDTs in Carcharhiniformes, Lamniformes and Rajiformes, concentrations were higher than in muscle tissue, which highlights the risk from consuming any elasmobranch product. The consumption of elasmobranchs is thus a global health concern, especially in commonly traded species, such as smooth and scalloped hammerheads, short fin mako and blue sharks with the highest concentrations. The risks associated with the consumption of elasmobranch products makes it essential that governments, regulators and seafood inspectors identify and track products that are sold in their country as well as the products that are imported and exported.

6. Knowledge gaps and future recommendations

This review was performed on 176 studies focussing on pollutants in elasmobranchs published between 1999 and 2019. Elevated concentrations were observed for common pollutants such as Hg, Cd, DDT and PCBs, although very little is known about emerging toxic pollutants such as PFAS, dioxin-like-compounds, and halogenated flame retardants. Even for commonly reported pollutants, the limited number of studies indicates that there is a huge gap in our knowledge on the health impacts of pollutant exposure in sharks, rays and skates. With their diverse and complicated life history, comparing elasmobranchs to other taxa such as marine mammals and bony fish could mean we are not accurately assessing their health risks. Most of the studies that discussed the potential health risks in elasmobranchs found that there was little or no evidence to prove these risks, though the high concentrations found in this study suggest that their health could be greatly impacted. There was also a greater focus on the risk to humans and so there is a critical need to understand the effect of these contaminants in elasmobranchs. Global trends and long-term changes in pollutant concentrations (i.e. further evidence of bioaccumulation) could not be inferred as there was not much consistency between species and pollutants studied. We suggest the development of a database, such as the Global Biodiversity Information Facility (GBIF, 2020), where all data on pollutants in elasmobranchs can be collated to determine trends over time, between species, taxa, gender, age, size, geographic location, etc.

Future studies should aim to focus their research on areas that have received less attention (e.g. the South Pacific, Indian Ocean and Red Sea) in order to accurately identify the global threats to elasmobranchs. This is especially crucial as in combination with threats from pollutant exposure, overfishing, habitat loss, and climate change, there may be an accelerated loss of already vulnerable species. There is also a need for biomonitoring programs that aim at providing long term information on the bioaccumulation and exposure risks of pollutants in elasmobranchs, as well as the threats for humans that consume elasmobranch related products.

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