Journal Pre-proof

Impacts of water pollutants on chondrichthyans species from South America: A review

Sabrina N. Fuentes, M. Constanza Díaz Andrade, Cynthia A. Awruch, Ana C. Moya, Andrés H. Arias

PII: S0045-6535(23)00529-5

DOI: https://doi.org/10.1016/j.chemosphere.2023.138262

Reference: CHEM 138262

To appear in: *ECSN*

Received Date: 29 November 2022

Revised Date: 18 February 2023

Accepted Date: 26 February 2023

Please cite this article as: Fuentes, S.N., Díaz Andrade, M.C., Awruch, C.A., Moya, A.C., Arias, André.H., Impacts of water pollutants on chondrichthyans species from South America: A review, *Chemosphere* (2023), doi: https://doi.org/10.1016/j.chemosphere.2023.138262.

Authors contribution

Sabrina N. Fuentes: Conceptualization, methodology, formal analysis, investigation, writing - Original Draft, visualization.

M. Constanza Díaz Andrade: conceptualization, methodology, investigation, writing – review, and editing, supervision, funding acquisition.

Cynthia A. Awruch: writing - review and editing, and supervision.

Ana C. Moya: Writing - Review and Editing

Andrés H. Arias: writing - review and editing, and supervision.

IMPACTS OF WATER POLLUTANTS ON CHONDRICHTHYANS SPECIES FROM SOUTH AMERICA: A REVIEW

Sabrina N. Fuentes [a,1,*], M. Constanza Díaz Andrade [a,b,1], Cynthia A. Awruch [c,d,*] , Ana C. Moya [a,b], Andrés H. Arias [e,f]

[a] Instituto de Ciencias Biológicas y Biomédicas del Sur (INBIOSUR – CONICET/UNS), San Juan 671, 8000, Bahía Blanca, Argentina.

[b] Departamento de Biología, Bioquímica y Farmacia (DBByF, UNS) San Juan 670, 8000, Bahía Blanca, Argentina.

[c] Centro Para el Estudio de Sistemas Marinos (CESIMAR – CENPAT- CONICET), Bv. Almirante Brown 2915 U9120ACD, Puerto Madryn, Argentina.

[d] School of Natural Sciences and Institute for Marine and Antarctic Studies (IMAS), College of Sciences and Engineering, University of Tasmania, Hobart, Tasmania, Australi

[e] Departamento de Química, Área III, Universidad Nacional del Sur, Av Alem 1253, 8000, Bahía Blanca, Argentina.

[f] Instituto Argentino de Oceanografía (IADO – CONICET/UNS), Camino La Carrindanga km 7.5, 8000, Bahía Blanca, Argentina.

* Corresponding author

E-mail address: sabrina.n.f@hotmail.com. Cel: +54 291 4595100 -int 2436 (Argentina). Postal address: 8000. *E-mail* address: awcynthia@cenpat-conicet.gob.ar. Cel: +54 9 280 4007651 (Argentina). Postal address: U9120ACD.

[1] Joint first authorship

Highlights

- There is an important knowledge gap about the possible effects of pollutants on Chondrichthyan's health in South America.
- The majority of South American regions have received very little or no attention regarding pollutants on Chondrichthyan species.
- South American Chondrichthyans have the potential to serve as good sentinel species to explore the health of the aquatic ecosystems, in particular *Prionace glauca* and *Mustelus schmitii*.
- More than 20% of the studies, reported contamination levels above recommended safety limits for Human consumption.

Abstract

This is the first research which extensively compiles all the available scientific literature on the presence of trace metals (TMs), persistent organic pollutants (POPs), and plastic debris in Chondrichthyan species inhabiting South America (including the Atlantic and Pacific Oceans), providing an insight into Chondrichthyans as bioindicators of pollutants as well as the impacts of pollutant exposure on the organisms. Seventy-three studies were published in South America between 1986 and 2022. While 68.5% focused on TMs, 17.8% on POPs, and 9.6% on plastic debris. Brazil and Argentina were at the top in terms of the number of publications; however, there is an absence of information regarding pollutants for Chondrichthyans in Venezuela, Guyana, and French Guiana. Of the 65 Chondrichthyan species reported, 98.5% belong to the Elasmobranch group, and 1.5% from the Holocephalans. Most studies focused on Chondrichthyans of economic importance, and the most analyzed organs were the muscle and liver. There is a lack of studies on Chondrichthyan species with low economic value and critical conservation status. Due to their ecological relevance, distribution, accessibility, high trophic position, capacity to accumulate high levels of pollutants, and the number of studies published, *Prionace glauca* and *Mustelus schmitii* seem to be adequate to serve as bioindicators. For TMs, POPs, and plastic debris there is a lack

of studies focusing on the pollutant levels as well as their effect on Chondrichthyans. Future research reporting TMs, POPs, and plastic debris ocurrences in Chondrichthyan species are required in order to increase the scarce databases about pollutants in this group, with a clear need for further research on the responses of chondrichthyans to pollutants, as well as making inferences about the potential risks to the ecosystems and human health.

Keywords: Elasmobranchii; Holocephali; persistent organic pollutants; trace metals; plastics debris.

1. Introduction

The rapid advancement of urbanization and industrial activities, along with the expansion of the agricultural frontier, have generated a progressive degradation of aquatic ecosystems. Globally, trace metals (TMs), persistent organic pollutants (POPs), crude oil, and marine debris (e.g., plastics or microplastics), constitute the most common marine pollutants introduced by human activities (United Nations Environment Program, 2022). At present, the toxicity and adverse effects of these contaminants on the marine environment are a matter of great concern and represent a growing threat to human health and biodiversity.

In the last three decades, the interest in using marine organisms as bioindicators of environmental pollution for ecological and human health risk assessment has significantly increased (Stankovic et al., 2014; Alves et al., 2022; Provenza et al., 2022; Dong et al., 2022; Ahmadi et al., 2022). The Class Chondrichthyes (commonly known as cartilaginous fishes) includes many suitable candidates to serve as bioindicators of anthropogenic contamination, with a broad range of endocrine, reproductive, biotransformation, oxidative stress, osmoregulation, energy metabolism-related, stress proteins, neuromuscular, histopathological, and morphological biomarkers available (Chierichetti et al., 2021; Alves et al., 2022).

The Chondrichthyan group constitutes one of the oldest and most ecologically diverse vertebrate lineages (Dulvy et al., 2014), comprising more than 1000 species divided into two subclasses; the Elasmobranchii (sharks, skates, and rays) and the Holocephali (chimaeras) (Dulvy et al., 2021). Chondrichthyes inhabit all the world's oceans (Compagno, 1990), and even are found in estuaries and rivers (Ebert et al., 2013; Lucifora et al., 2015). In addition, this group is widely distributed from shallow coastal waters to deep-sea floors (Compagno, 1990). Many cartilaginous fishes are top-level predators, playing an important role in the top-down control of coastal and oceanic ecosystems structure and function (Stevens et al., 2000; Cailliet et al., 2005; Ferretti et al., 2010; Dulvy et al., 2014). As a result of their longevity and high trophic position, Chondrichthyan species are highly susceptible to bioaccumulate and biomagnify high levels of environmental contaminants throughout their lifetime (Suedel et al., 1994; Dwivedi and Trombetta, 2006; Lyons et al., 2014). This is of great concern considering that the number of Chondrichthyan species in threatened categories (critically endangered, endangered, or vulnerable) has doubled in the last seven years (Dulvy et al., 2014, 2021), and many species represent a substantial source of revenue and food to many people worldwide (Bernardo et al., 2020).

South America is a complex area of great geographical, biological, and climatic diversity comprehending several biomes (Delgado et al., 2022). This region includes five of the 17 megadiverse countries around the world: Peru, Ecuador, Colombia, Venezuela, and Brazil (Mittermeier et al., 1997). This high diversity is also evident in its chondrichthyan richness, with more than 400 species known (Becerril-Garcia et al., 2022). Most of these species have cultural, ecological, and economic importance, due to their role in ecosystem functioning, fisheries, and tourism (Becerril-Garcia et al., 2022). In addition, South America is considered one of the most vulnerable areas worldwide due to anthropogenic impacts (Barletta et al., 2010), with a high number of threatened chondrichthyan species, particularly in Brazil and Uruguay (Dulvy et al., 2021).

Similarly to the rest of the world, the COVID-19 pandemic has exacerbated the plastic pollution problem in South America. The high consumption of single-use elements (gloves, face protectors, protective suits, safety shoes) made up of polymeric materials, leads to a larger pool of microplastics in the marine environment, likely affecting the future health condition of the marine organisms (Arias et al., 2019). Additionally, South America has been affected by POPs from different sources, including pesticides used for agricultural and/or sanitary purposes, industrial chemicals, such as polychlorinated biphenyls (PCBs), and industrial by-products, as polychlorinated dibenzo-p-dioxins and -furans (PCDD/Fs) (UNEP, 2002a). Furthermore, high levels of TM pollutants were reported in South American estuaries, which may pose a significant risk to the biota (Barletta et al., 2019). Trace metal concentrations above the permissible levels for human consumption were already reported in many teleost fish species such as *Brevoortia aurea*, *Odontesthes argentinensis*, and *Micropogonias furnieri*, (Barletta et al., 2019; and references therein).

To date, although three global reviews have been carried out on pollutants in Chondrichthyes (Bezerra et al., 2019; Tiktak et al., 2020; Consales and Marsili, 2021), the information presented from South America was incomplete and restricted only to Brazilian publications. In this sense, we present the first research which extensively compiles all the available scientific literature on the presence of trace metals (TMs), persistent organic pollutants (POPs), and plastic debris in Chondrichthyan species inhabiting South America (including the Atlantic and Pacific Oceans). In addition, to lay the basis for the implementation of management and conservation strategies for chondrichthyan species evaluate which Chondrichthyan groups or species are good candidates to serve as bioindicators, identifying gaps and vacancy topics for future research.

2. Materials and methods

Following the methodology proposed by Awruch et al. (2019), a bibliometrical analysis to identify research papers on aquatic contamination (trace metals, persistent organic pollutants, and plastic debris) in South American Chondrichthyans was undertaken. In order to guarantee the most comprehensive dataset and avoid data duplication, three online databases, Google Scholar, Scopus, and ScienceDirect, were used as platforms to identify the following search terms in titles, keywords, and abstracts: “shark”, “stingray”, “skate”, “holocephalans”, “elasmobranch”, “trace metal”, “persistent organic pollutant” and “plastic” in different combinations to refine results. The selection criteria included articles solely from South American countries (Chile, Peru, Ecuador, Colombia, Venezuela, Surinam, Guyana, French Guiana, Brazil, Uruguay, and Argentina) published in the English, Spanish, and Portuguese languages. The search results included all studies published from 1986 (the oldest record) to October 2022. A total of 73 studies were identified and selected. Some articles were found based on the studies identified through the tracking back search, for example, two additional articles were added based on the systematic review published on trace metals in sharks and rays (Perez et al., 1986; Scapini et al., 1996). For each study, recorded information included: references, species of study, pollutant type and concentration (e.g. DDT, Hg), study area (e.g. Argentina, Brazil), and target medium (e.g. liver, muscle).

3. Results and Discussion

3.1. South American Chondrichthyan research: general information

The present review yielded 73 studies on aquatic contamination on Chondrichthyan species assessed for pollution in South America, published between 1986 and 2022 (October). A detailed list of the Chondrichthyan species reported in this study is presented as supplementary material, along with study areas, types of contaminants, target medium, and references (Table S1).

Of the total number of studies, 68.5% (n = 50) were focused on trace metals (TMs), 17.8% (n = 13) on persistent organic pollutants (POPs), and 9.6% (n = 7) on plastic debris (Fig. 1a). From these studies, only one included ^{210}PO (polonium isotope), and two included PPCPs (emerging pesticides, pharmaceuticals, and personal care products) (Fig 1a). Plastic debris, POPs, and TMs results will be presented and discussed in Section 3.3.

There is a growing trend in the articles published between 2007 and 2021, with a peak in the number of articles from 2019 to 2021, especially regarding TMs and POPs (Fig. 1a). This peak could be the result of more time available to write as a consequence of a decrease in other work-related activities (e.g. fieldwork) due to the COVID-19 restrictions.

The majority of the studies were done in Brazil (n = 45) and Argentina (n = 13), while the least studied areas were Peru (n = 3), Chile (n = 3), Ecuador (n = 3), Colombia (n = 3), Suriname (n = 1), and Uruguay (n = 1) (Fig. 1b). Only one study reported information from two countries, in Peru and Chile. No records were found in the coastal waters of Venezuela, Guyana, and French Guiana (Fig.1b). Considering that the South America region contains highly productive marine ecosystems including two of the 15 highest fishery-producing countries in the world (Peru and Chile, FAO, 2020), it is an important goal that future researches focus on regions that have received very little attention in order to identify the global threats to marine organisms, as well as possible impacts for human consumption.

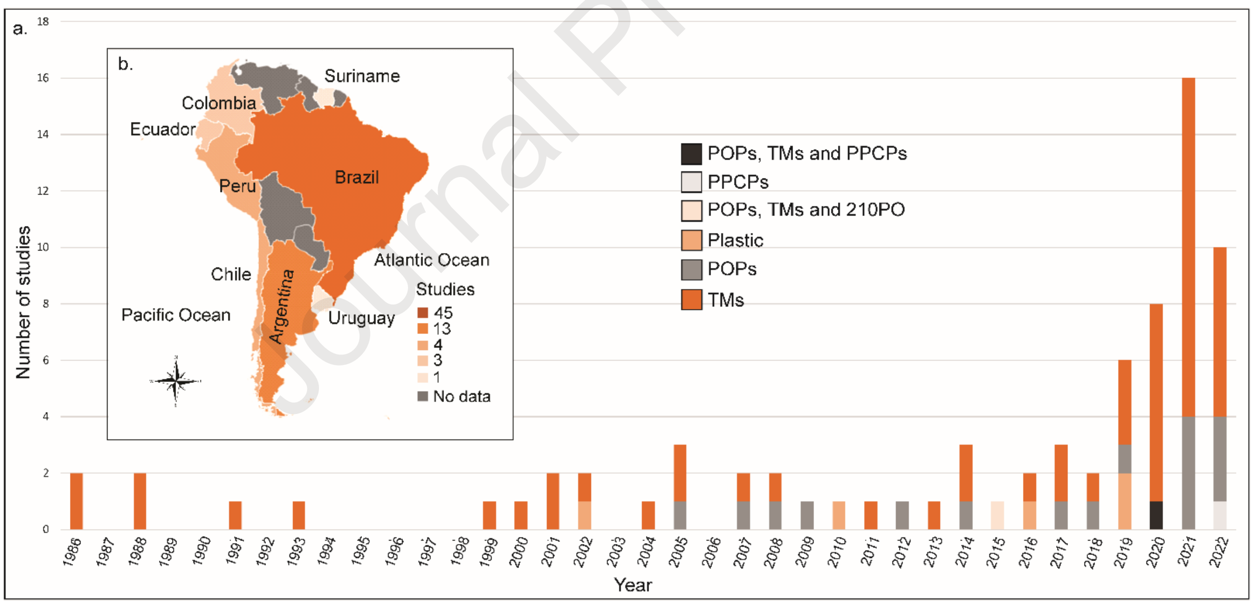

Figure 1. a. Number of studies on TMs (trace metals), POPs (persistent organic pollutants), plastics, PPCPs (emerging pesticides, pharmaceuticals, and personal care products), and ^{210}PO (polonium isotope) in different Chondrichthyan species from South America, published between 1986 and 2022. b. Geographic distribution on pollutant studies in Chondrichthyan species grouped by country.

Different organs, tissues, and fluids have been used to measure contaminants in Chondrichthyan species, including blood, brain, gills, kidney, liver, rectal gland, muscle, ampullae of Lorenzini, yolk, fin, stomach and uterine contents, gonads, electric organs, and even embryos. Muscle and liver were the most common organs analyzed, with 36 and five studies, respectively. Twenty studies combine muscle and liver examinations with other target organs (e.g., gill, gonads, and brain). Pollutant accumulation in Chondrichthyans organs has been focused mainly on muscle and liver tissues (e.g., La Colla et al., 2021; Corrêa et al., 2022) due to their importance for human consumption (Marcovecchio et al., 1991; Tiktak et al., 2020). For example, shark species are used as human food (meat, fins' soup), in the industry (skin, shark liver oil), and for medicinal purposes (vitamin A, cancer cure) (Kibria and Haroon, 2022). Furthermore, the liver plays an important role in vital functions, and basic metabolism and is the principal site of accumulation, biotransformation, and excretion of pollutants in fish (Nunes et al., 2008). To date, few studies are focused on gills in Chondrichthyan from South America (n = 9; see TS1). However, these organs are continuously and directly exposed to contaminated water. If we take into account that gills are implicated in a great number of physiological roles, such as respiration and osmoregulation, these organs can be good candidate biomarkers for aquatic contaminants (e.g., De Boeck et al., 2001, 2007).

3.2. South American Chondrichthyans research by species

A total of 65 Chondrichthyan species were reported, including 98.5% (n = 64 species) from the Subclass Elasmobranchii (sharks, rays, and skates) and 1.5% (n = 1) from the Subclass Holocephalans (chimaeras) (Fig. 2 a, b).

Within the Elasmobranchii, the Selachimorpha (sharks) were the most diverse superorder, with a total of 43 species (66.2%) reported (Fig. 2b). This group included 18 genera belonging to the orders Carcharhiniformes (30 species), Lamniformes (6 species), Squaliformes (3 species), Squatiniformes (2 species), Hexanchiformes (1 species), and Orectolobiformes (1 species) (Fig.

2c). The Carcharhiniformes were the most abundant in terms of published articles (n = 51), with the majority of the research based on TMs (n = 38), followed by plastic debris (n = 7), and POPs (n = 6). In addition, the most reported species were *Prionace glauca* (21.9% of the total number of studies), *Mustelus schmitii* (17.8%), and two species of the genus *Rhizoprionodon* (*R. porosus*, *and R. lalandii*; with 13.7% and 12.33% respectively). Except for *P. glauca*, which is one of the most wide-ranging oceanic shark species (Last and Stevens, 2009; Ebert et al., 2013), the other three, are endemic, inhabiting the Western Central and Southwest Atlantic Oceans (Oddone et al., 2005; Ebert et al., 2013). These species are frequently exploited throughout their range of distribution by artisanal and commercial fisheries due to the high economic value of their fins and meats for the local market and international trade (Segura and Milessi, 2009; Tagliafico et al., 2015; Fields et al., 2017).

A total of 21 species (32.3%) were recorded for the Superorder Batoidea (rays and skates) (Fig. 2b). This group included 14 genera from the orders Myliobatiformes (9 species), Rajiformes (8 species), Rhinopristiformes (3 species), and Torpediniformes (1 species) (Fig. 2c). The order Myliobatiformes was the most studied (n = 11), with the majority of the research focused on TMs (n = 7), followed by POPs (2) and plastic debris (2). In addition, *Pseudobatos horkelii*, and *Hypanus guttatus* were the most represented, with 8.1% and 6.7% of the total number of studies, respectively. *Pseudobatos horkelii* belongs to the order Rhinopristiformes and is distributed in the Southwest Atlantic from Rio de Janeiro, Brazil, to northern Argentina (Menni and Stehmann, 2000, Last et al., 2016). *Hypanus guttatus* belongs to the order Myliobatiformes and is distributed in the Western Central and Southwest Atlantic Oceans, from Mexico to Panamá and Brazil (Barletta and Correa, 1989; Last et al., 2016). The economic importance of *P. horkelii* and *H. guttatus* is restricted to the local meat market (Coelho et al., 2020).

The Holocephalans (chimaeras), were the less studied group (n = 3), represented only by one species, *Callorhinchus callorhynchus* (Fig. 2a). Articles were based on TMs (n = 2) and POPs (n = 1). *Callorhinchus callorhynchus* is distributed from Río de Janeiro, Brazil to southern

Patagonia in the Southwest Atlantic Ocean, and from Ecuador to Chile in the Southeast Pacific Ocean (Di Giacomo and Perier,1996). In addition, *C. callorhynchus* is utilized for its flesh and fins in the local and international trade (INIDEP 2018, SUBPESCA 2018).

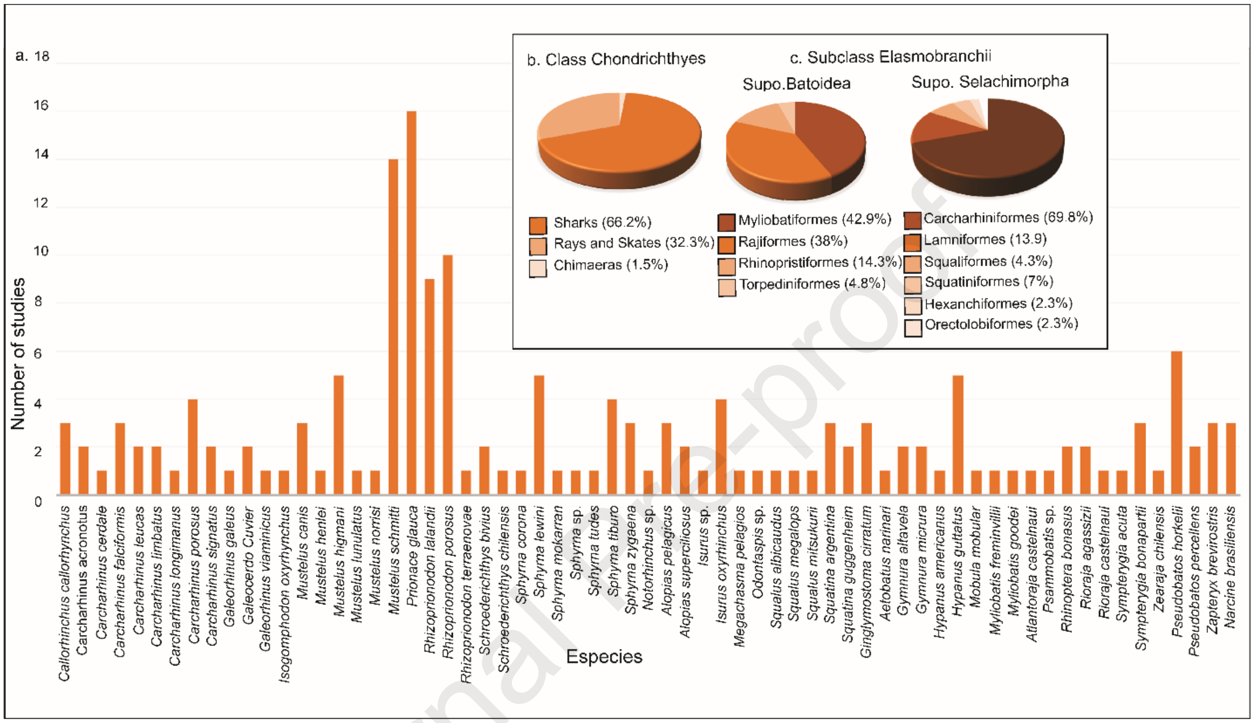

Figure 2. Pollutant studies in South American Chondrichthyans. a. Total number of pollutant studies per Chondrichthyes species; b. Percentage of Chondrichthyan species with studies carried out on anthropogenic contaminants divided by groups; c. Percentage of elasmobranch species with studies carried out on anthropogenic contaminants grouped by superorder and order.

Recently, Tiktak et al. (2020), suggested a possible bias in the total number of worldwide publications on pollutants in Chondrichthyans towards shark species of fishery significance. This situation is also evident in South America, where most studies were focused on shark species, of economic importance, as *P. glauca* and *M. schmitti* (Fields et al., 2017; Segura and Milessi, 2009).In addition, there is a lack of studies based on pollutants in many Chondrichthyan species in this region, such as *Squatina armata*, *Mustelus minicanis*, *Dipturus chilensis*, and *Hydrolagus matallanasi* (Ebert et al., 2013; Grijalba et al., 2009; Concha et al., 2019). This is of particular concern, considering that these species, with low economic value and low priority for research and management funds, have restricted geographic distributions and critical conservation status (IUCN, 2022).

3.3. South American Chondrichthyan research by pollutant

3.3.1. Plastic debris

Only seven studies identified and quantified the presence of plastic debris in Chondrichthyan species. All specimens were collected from the Southwest Atlantic coast of Brazil (Table S1, S2). Of the total of articles, three identify macroplastics in the gill or mouth region, and stomach content of the sharks, *Rhizoprionodon lalandii* and *Prionace glauca* (Sazima, 2002; Cardoso and Vooren, 2010; Barreto et al., 2019; Fernández and Anastasopoulou, 2019). The macroplastics assessed were, plastic debris rings, plastic straps, multifilament gillnet, plastic bags, entanglements with bait box straps, and synthetic boots (Sazima, 2002; Cardoso and Vooren, 2010; Barreto et al., 2019; Fernández and Anastasopoulou, 2019). On the other hand, only three studies identified and quantified microplastic particles in the stomach contents of the sharks *Mustelus canis, R. lalandii,* and *Mustelus higmani*, and in the rays, *Narcine brasiliensis*, *Rhinoptera bonasus,* and *Hypanus guttatus* (Miranda and Carvalho-Souza, 2016; Pegado et al., 2018, 2021). According to Pegado et al. (2018), microplastic particles sizes ranging from 0.38 to 4.16 mm. In addition, they found a positive correlation between fish standard length and the number of particles present in the gastrointestinal tracts, which could be related to the generalist feeding strategies of adults (Pegado et al., 2018). Added to this, Pegado et al. (2021), classified the microplastic particles according to their abundance, shape, and color, being fibers the most frequent item, blue the most frequent color, and Polyethylene Terephthalate (PET) the most frequent polymer. Miranda and Carvalho-Souza (2016), reported plastic resin pellets and classified them according to their sizes (1 to 5 mm), shapes (cylindrical), and colors (ranging from clear to white and yellowish).

Although the extent of plastic debris (microplastics and macroplastics) effects on South American Chondrichthyans species are still practically unknown, tissue damage, and lesions (in gill and mouth) that compromise vital activities, such as breathing, swimming, and eating were reported on *Rhizoprionodon lalandii* and *Prionace glauca* (Sazima, 2002; Cardoso and Vooren, 2010; Barreto et al., 2019).

To support effective prevention and conservation efforts in response to this global problem is essential to understand the spatial and temporal patterns of plastic pollution in aquatic ecosystems and its effects on the organisms (Yao et al., 2019). To date, the degree of bioaccumulation of plastic debris in Chondrichthyan species from South America, as well as the biomagnification data within the trophic nets, are practically unknown. Considering the rapid increase in plastic pollution in South American waters, it is imperative to delineate studies assessing the impact of plastic pollution on Chondrichthyan species.

3.3.2. Persistent Organic Pollutants (POPs)

There were 14 articles reporting POPs in South American Chondrichthyan species (Table S3). The majority focused on sharks (n = 11), followed by rays (n = 5), and chimaeras (n = 1). Species were collected from the Southwest Atlantic coast of Brazil (10 species), followed by Argentina (2 species) and the Southeast Pacific coast of Chile (1 species) (Table S1). Reported POPs include industrial chemicals, such as polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), polybrominated diphenyl ethers (PBDEs), polychlorinated terphenyls (PCTs), hexachlorobenzenes (HCBs), and tetrachloronaphthalenes (TCNs), and pesticides as dichlorodiphenyltrichloroethane (DDTs), hexachlorocyclohexanes (HCHs/lindanes), atrazine, chlorothalonil, chlorpyrifos, dichlofluanid, diuron, trifluralin, drins, endosulfans, chlordane, and mirex (Table S3). Of the total number of studies, DDTs, PCBs, and PAHs were the most reported pollutants, being at least one of them present in each article. These contaminants are characterized by their toxicity, mutagenic and carcinogenic activity, as well as by their strong persistence in the environment, and high hydrophobicity which leads them to be incorporated throughout the food chain. Although the use or manufacture of these POPs is prohibited or restricted, they have been incorporated into the list of priority organic pollutants whose discharge must be monitored (Directive n° 76/464) (Lara Martín et al., 2005). The most analyzed tissues were the muscle and liver, representing 50% and 42.8% of articles in this category, respectively. Other reported target mediums include blood, gills, ovaries, eggs, and embryos. Maximum mean concentrations and range of the most reported POPs detected in different target mediums of Chondrichthyan species are shown in Table S4.

The highest concentrations of PCBs and DDTs were reported in the liver of the ray *Gymnura altavela* (12,469.7 ng g^{-1} l.w and1808.03 ng g^{-1} l.w respectively) from the coast of Rio de Janeiro, Brazil (Table S4). Nevertheless, the highest PAHs concentrations were reported in the muscle of the shark *Pseudobatos horkelii* (2134.8 ng g^{-1} w.w) from Praia do Cassino, Brazil (Martins et al., 2020) (Table S4). This atypical high concentration in the muscle compared to the levels reported in the liver of *P. horkelii* (1452.8 ng g-1 w.w) may be suggest a chronic exposure to PAHs in the sampling area and in consequence a risk to the species and human health (Martins et al., 2020) (Table S4). Considering that POPs tend to accumulate in lipid-rich tissues (Logan, 2007), and the liver has much higher percentages of lipids than other organs, caution should be exercised when making comparisons between POPs concentrations in different target medium (Cascaes et al., 2014).

Many ecological and biological parameters, such as habitat use, diet, trophic position, age, sex, body size, season, lipid content, and mobility, play an important role in the bioaccumulation patterns of pollutants in fish (Van der Oost et al., 2003). Changes in POPs concentration varied according to their feeding habits, sex, and maturity stage. For example, Cascaes et al. (2014), recorded higher POPs (PCBs, DDTs, and PBDEs) concentrations of the coastal demersal shark *Rhizoprionodon lalandii*, showing significant differences in POPs accumulation compared to oceanic species that feed in deeper waters. According to Chierichetti et al. (2021), in the chimaera *C. callorhynchus*, females presented higher values of OCPs (organochlorine pesticides) than males, and mature individuals showed higher PCBs concentration than immature ones. In addition, Correa et al. (2022), reported higher POPs (PCBs, DDTs, HCH, HCB, and Mirex) concentrations in adults than in juvenile specimens, of the skate *Rioraja agassizii*. However, positive correlations between maturity stages and POPs levels in Chondrichthyans species were not always observed. As an example, Recabarren-Villalón et al. (2021), reported higher concentrations of PAHs in juvenile individuals than in mature ones, which could be related to the differential use of habitat during their life cycle. On the other hand, only one study evaluated the exposure of PAHs in marine environments with different degrees of pollution from the Chilean coast, using two important tools, the liver 7-ethoxyresorufin-O-deethylase dealkylation (EROD) activity and the Fluorescent Aromatic Compounds (FAC) in the bile on the shark *Schroederichthys chilensis* (Fuentes-Ríos et al., 2005).

Although POPs studies have not investigated the physiological effects on South American chondrichthyan species, Martins et al. (2021a), reported a moderate capacity of maternal offloading of PAHs in the sharks *Pseudobatos horkelii*. Polycyclic aromatic hydrocarbons (PAHs) are known to be able to cause many deleterious effects in the early-life stage of development of several species (e.g., embryonic narcosis, cardiac function impairment in embryos among others) (Barron et al., 2004; Incardona et al., 2004). In this context, these investigations are highly important in order to establish baseline ecotoxicological data for *P. horkelii*, listed by IUCN as critically endangered. Regarding the potential risk of POPs on human health, only three studies evaluated the associated risk with the consumption of *Mustelus schmitii* in Argentina by cancer risk analysis; however, the results concluded that PAHs and organochlorine pesticides levels in this edible shark would not pose a risk to human health in the region (Recabarren-Villalón et al., 2021; Oliva et al., 2017, 2022).

Considering their persistence, potential for long-range transport, ability to bioaccumulate and biomagnify in the organisms, as well as the potential risk of POPs on the ecosystem and human health (United Nations Environment Programme – UNEP, 2002a), the remarkable scarcity of data about POPs contamination effects on Chondrichthyan species in South America is disturbing and highlights the need for studies on this area.

3.3.3. Trace metals (TMs)

A total of 52 studies reported TMs in Chondrichthyans, 78.85% focused on sharks (n = 41), 9.61% on rays (n = 5), 7.7% on sharks and rays (n = 4), 1.92% on rays and chimaeras (n = 1), and 1.92% on sharks, rays, and chimaeras (n = 1) (Table S5). The majority of the species were collected from Brazil (49) followed by Colombia (9), Argentina (9), Ecuador (6), Chile (4), Suriname (4), Peru (2), and Uruguay (1) (Table S1). Fifty-five TMs were reported, being mercury (Hg) the most commonly TM measured (n = 45), representing 61.6% of the total number of the studies reported in this review, followed by cadmium (Cd) (n = 18; 34.6%), and lead (Pb) (n = 17; 32.7%) (Table S5). Due to its high toxicity, strong bioaccumulation, and biomagnification through food chains, Hg represents one of the most potentially hazardous pollutants in the aquatic ecosystem (Julio et al., 2022). In this context, the use of aquatic organisms with long-lived, and high trophic positions, as Chondrichthyans, represents an essential tool to monitor Hg concentrations in the aquatic environment and Hg exposure to human consumption (Verhaert et al., 2018). When looking at target mediums, the muscle was the most analyzed tissue representing 94.2% (n = 49) of the published articles. Other reported target mediums include the liver, electric organs, gonads, yolk, uterine contents, brain, fins, stomach, kidney, Ampullae of Lorenzini, rectal gland, and gills (Table S1). The concentration of TMs (Hg, Cd, and Pb) detected in the muscle and liver of Chondrichthyan species are shown in Table S6.

The majority of the TM studies in Chondrichthyan species were focused on determining their levels in different target mediums and exploring if possible differences in TMs could be attributed to several factors, such as habitat, dietary differences, sex, maturity stages, maternal transfers, and the metabolic rate related to ontogenetic processes (e.g., Marcovecchio et al., 1991; Mull et al., 2012; Lyons et al., 2013; Lacerda et al., 2000). For example, Maurice et al. (2021) reported higher concentrations of Hg and monomethyl-Hg (MMHg, the most toxic mercury species) in the sharks *Alopias superciliosus*, *Alopias pelagicus*, *Sphyrna lewini*, *Carcharhinus longimanus*, *Prionace glauca*, and *Carcharhinus falciformis*, concluding that these high levels are mostly influenced by body size, age, and dietary habits. Moura et al. (2020) and Julio et al. (2022), reported a significant positive correlation between Hg concentrations and body size in the ray *Hypanus guttatus* and in the shark *Rhizoprionodon porosus*. However, a negative correlation between body size and Hg levels was reported for the sharks *Sphyrna zygaena* (Gonzalez-Pestana et al., 2017), *P. glauca* (Carvalho et al., 2014), and *Mustelus norrisi* (Penedo de Pinho et al., 2002). In general, Hg shows a positive correlation with body size, age, and trophic position (Boening, 2000, Lacerda et al., 2000). Reports on other TMs in *P. glauca*, showed no significant differences in Cd and Pb levels between sexes and seasonality (Lopez et al., 2013; Reategui-Quispe and Pariona-Velarde, 2019; Castro-Rendón et al., 2022; Cordero-Maldonado et al., 2022). One explanation for this could be that females and males share the same feeding items (Lopez et al., 2012).

The impacts of TMs on Chondrichthyan species were reported only in five studies (Pimienta et al., 2005; Wosnick et al., 2021a, b; Hauser-Davis et al., 2020b, 2022). Effects of TMs were measured using diverse biomarkers such as Metallothioneins (MTs) (Pimienta et al., 2005; Wosnick et al., 2021b; Hauser-Davis et al., 2022) and reduced glutathione (GSH), (Wosnick et al., 2021b) in muscle and liver, and serum biomarkers (urea, lactate, ALT, triglycerides, alkaline phosphatase, and phosphorus) in gills, liver, and rectal gland (Wosnick et al., 2021a). Many authors provided a baseline for understanding the maternal offloading of trace metals in the sharks *Rhizoprionodon lalandii*, *R. porosus, Mustelus higmani*, *Squalus albicaudus,* and *Pseudobatos horkelii*, and in the ray *Narcine brasiliensis* (Amoris-Lopes et al., 2019, 2020; Souza-Araujo et al., 2020; Hauser-Davis et al., 2020a, 2022; Martins et al., 2022a; Willmer et al., 2022). Considering that toxic actions of TMs are particularly pronounced during the embryonic developmental phases adversely affecting various metabolic processes (e.g., developmental retardation, morphological and functional deformities, or death) (Authman et al., 2015), these investigations are key to foreseeing the future of Chondrichthyan species affected by TMs.

More than 20% of the studies (24.6%, n = 18), reported concentrations of Hg, Cd, Cr, Pb, and As above the maximum level permissible for human consumption (Table S6). It is important to mention, that due to the very limited number of studies focused on TM levels in the liver, the results are focused on muscle tissue concentrations. The maximum total Hg contamination limit for safe consumption is 1.0 mg kg^{-1} for predatory fish species (FAO and WHO, 2011; USEPA, 2000). The maximum higher average Hg concentration found in the present review was observed in the Superorder Selachimorpha and was highly above this limit (3.12 mg kg^{-1} wet weight) (Fig. 3). Contrary to this, the Superorder Batoidea presented the maximum higher average Cd and Pb concentrations (2.16 mg kg^{-1} w.w and 0.72 mg kg^{-1} w.w, respectively) compared to the levels reported for the Selachimorpha species (0.18 mg kg^{-1} and 0.06 mg kg^{-1} w.w, respectively) (Fig. 3). These levels are alarming, taking into account that the maximum permissible levels of Cd and Pb in muscle tissue for fish consumption are 0.05 mg kg^{-1} and 0.3 mg kg^{-1}, respectively (European Union Standards, 2006). The higher average Cd and Pb concentrations reported in the Superorder Batoidea could be related to the life-history traits of these organisms, which is linked to the benthic bottom substrate of coastal areas, where trace metals often accumulate, increasing their exposure potential (Bezerra et al., 2019). In contrast, although the Hg concentration reported in this review seems to be higher in the Selachimorpha, the great difference in the number of publications between these two superorders makes it difficult to elaborate solid conclusions. Further studies on this metal in the Superorder Batoidea are required to see if this trend continues. Figure 3 shows the comparison of Hg, Cd, and Pb concentrations between the Superorder Selachimorpha and the Superorder Batoidea.

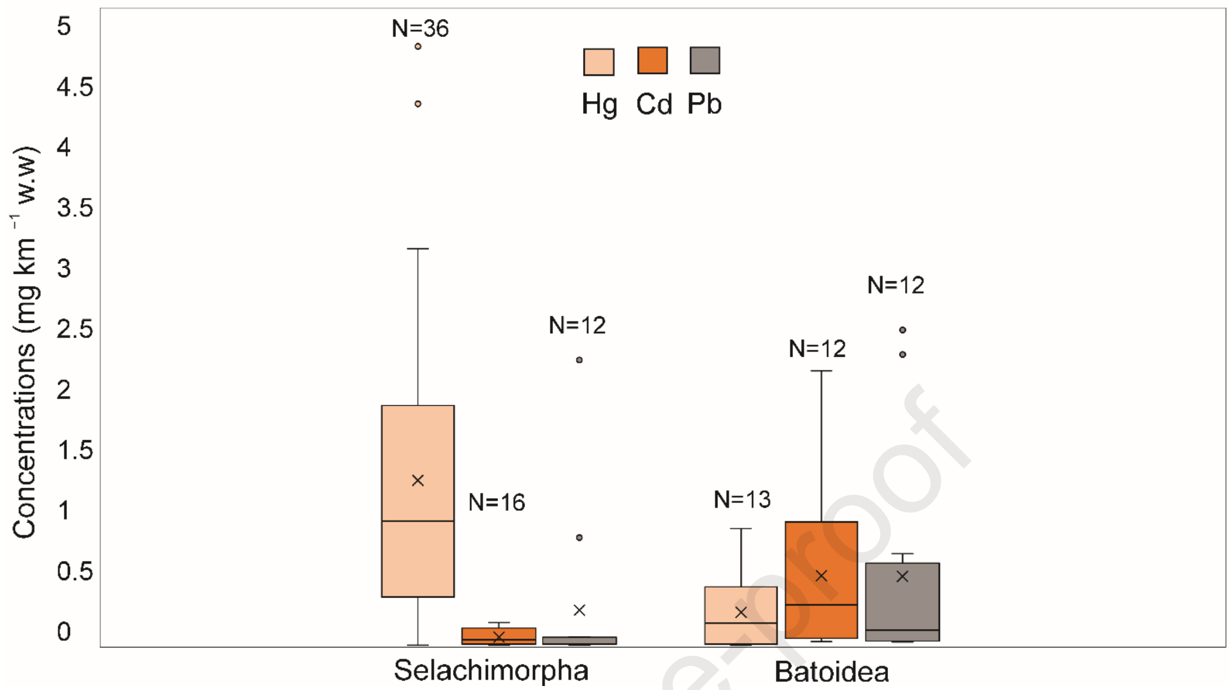

Figure 3. Concentrations of Hg (mercury), Cd (cadmium), and Pb (lead) in muscle for the superorder Selachimorpha and Batoidea reported in South America. Values are expressed in mg kg^{-1} on wet weight (w.w.). (box = standard deviation, medium line = median, upper and lower line = maximum and minimum values; circle = atypical values, N = number of species).

3.4. Conclusions

This paper revisits all the available information (1986-2022) on the presence of pollutants (plastic debris, POPs, and TMs) in Chondrichthyan species from South America, which includes a large number of top predators with high ecological and societal relevance, large distribution, accessibility, longevity, and capacity to accumulate environmental pollutants.

We demonstrated that there is a vast knowledge gap about the possible effects of the reported pollutants on Chondrichthyan's health, and highlight the importance of establishing connections between external levels of exposure to toxic substances, internal levels of tissue contamination, and the health adverse effects.

Given the easy accessibility and the number of studies targeting *Prionace glauca* for long-range pelagic areas and *Mustelus schmitii* for coastal areas, together with their ecological relevance and capacity to accumulate high levels of environmental pollutants, these two shark species seem to be good candidates to serve as bioindicators in South America.

Revisited data revealed a concern in regard to human exposure to TMs (mainly Hg, Cd, Pb, Cr, and As) by Chondrichthyan consumption. In this context, more studies are needed to fully understand the extent of human risk to Chondrichthyan consumption and caution should be taken when consuming Chondrichthyan meat from contaminated areas.

Furthermore, the majority of the South American regions have received very little or no attention regarding pollutants in Chondrichthyan species, thus, it is an important goal that future research focus on these regions in order to identify the global threats to marine organisms, as well as human consumption.

Then, future research is therefore required to increase the scarce databases about pollutants in cartilaginous fishes, with a clear need for further research on the responses of chondrichthyan species to pollutants, as well as making inferences about the potential risks to the ecosystems and human health, as well to adequately manage the species on an ecological and sanitary approach.

Declaration of competing interest

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

Acknowledgments

This work was supported by PGI 24/B286.

References

Ahmadi, A., Moore, F., Keshavarzi, B., Shahimi, H., Hooda, P.S., 2022. Bioaccumulation of selected trace elements in some aquatic organisms from the proximity of Qeshm Island ecosystems: Human health perspective. Mar. Pollut. Bull. 182, 113966. https://doi.org/10.1016/j.marpolbul.2022.113966.

Alarcón, C., Cubillos, L.A., Acuña, E., 2011. Length-based growth, maturity, and natural mortality of the cockfish *Callorhinchus callorhynchus* (Linnaeus, 1758) off Coquimbo, Chile. Environ. Biol. Fishes 92, 65-78. https://doi.org/10.22370/rbmo.2022.57.Especial.3201.

Alves, L.M., Lemos, M.F., Cabral, H., Novais, S.C., 2022. Elasmobranchs as bioindicators of pollution in the marine environment. Mar. Pollut. Bull. 176, 113-418. https://doi.org/10.1016/j.marpolbul.2022.113418.

Amorim-Lopes, C.A., Araujo, N.L. F., Rocha, L., Monteiro, F., Rocha, R.C.C., Saint'Pierre, T.D., Hauser-Davis, R.A., 2019. Toxic and essential metals in *Narcine brasiliensis* (Elasmobranchii: Narcinidae): a baseline ecotoxicological study in the Southeast Atlantic and preliminary maternal transfer implications. Mar. Pollut. Bull. 149, 110606. https://doi.org/10.1016/j.marpolbul.2019.110606.

Amorim-Lopes, C., Willmer, I.Q., Araujo, N.L., de Pereira, L.H.S., Monteiro, F., Rocha, R.C., Hauser-Davis, R.A., 2020. Mercury screening in highly consumed sharpnose sharks (*Rhizoprionodon lalandii* and *R. porosus*) caught artisanally in southeastern Brazil. Elem. Sci. Anth. 8, 1-13. https://doi.org/10.1525/elementa.022.

Arias, A.H., Ronda, A.C., Oliva, A.L., Marcovecchio, J.E., 2019. Evidence of microplastic ingestion by fish from the Bahía Blanca estuary in Argentina, South America. Bull. environ. contam. Toxicol. 102, 750-756. https://doi.org/10.1016/j.envpol.2021.118607.

Authman, M.M., Zaki, M.S., Khallaf, E.A., Abbas, H.H., 2015. Use of fish as bio-indicator of the effects of heavy metals pollution. J. Aquac. Res. Dev. 6, 1-13. http://dx.doi.org/10.4172/2155-9546.1000328.

Barletta, M.,Correa, M.F.M., 1989. Chondrofauna do complexo estuarino da baía de Paranaguá e adjacências, PR – Brasil. Levantamento e produtividade pesqueira. In: Summaries of the IV Meeting of the Work group on Fishes and Research of Sharks and Rays in Brazil, Tamandaré 23.

Barletta, M., Jaureguizar, A.J., Baigun, C., Fontoura, N.F., Agostinho, A.A., Almeida-Val, V.D., Corrêa, M.F.M., 2010. Fish and aquatic habitat conservation in South America: a continental overview with emphasis on neotropical systems. J. Fish Biol. 76, 2118-2176. https://doi.org/10.1111/j.1095-8649.2010.02684.x.

Barletta, M., Lima, A.R., Costa, M.F., 2019. Distribution, sources and consequences of nutrients, persistent organic pollutants, metals and microplastics in South American estuaries. Sci. Total Environ. 651, 1199-1218. https://doi.org/10.1016/j.scitotenv.2018.09.276.

Barreto, R., Bornatowski, H., Fiedler, F.N., Pontalti, M., da Costa, K.J., Nascimento, C., Kotas, J.E., 2019. Macro-debris ingestion and entanglement by blue sharks (*Prionace glauca* Linnaeus, 1758) in the temperate South Atlantic Ocean. Mar. Pollut. Bull. 145, 214-218. https://doi.org/10.1016/j.marpolbul.2019.05.025.

Barron, M.G., Carls, M.G., Heintz, R., Rice, S.D., 2004. Evaluation of fish early life-stage toxicity models of chronic embryonic exposures to complex polycyclic aromatic hydrocarbon mixtures. Toxicol. Sci. 78, 60-67. https://doi.org/10.1093/toxsci/kfh051.

Becerril-García, E.E., Arauz, R., Arellano-Martínez, M., Bonfil, R., Ayala-Bocos, A., Castillo-Géniz, J. L., Godard-Codding, C.A., 2022. Research priorities for the conservation of chondrichthyans in Latin America. Biol. Conserv. 269, 109535. https://doi.org/10.1016/j.biocon.2022.109535.

Bernardo, C., Corr, A.M., Lima, D., Paes, V., Foresti, F., Loose, R.H., Bornatowski, H., 2020. The label "Cação" is a shark or a ray and can be a threatened species Elasmobranch trade in southern Brazil unveiled by DNA barcoding. Mar. Policy 116. https://doi.org/10.1016/j.marpol.2020.103920.

Bernasconi, J., Cubillos, L., Acuña, E., Perier, R., Di Giácomo, E., 2015a. Crecimiento, madurez y mortalidad del pez gallo, *Callorhinchus callorynchus*, en el Golfo San Matías, Patagonia norte, Argentina. Rev. Biol. Mar. Oceanogr. 50, 283-298. https://doi.org/10.4067/S0718-19572015000300007.

Bezerra, M.F., Lacerda, L.D., Lai, C.T., 2019. Trace metals and persistent organic pollutants contamination in batoids (Chondrichthyes: Batoidea): A systematic review. Environ. Pollut. 248, 684-695. https://doi.org/10.1016/j.envpol.2019.02.070.

Boening, D.W., 2000. Ecological effects, transport, and fate of mercury: a general review. Chemosphere 40, 1335-1351. https://doi.org/10.1016/S0045-6535(99)00283-0.

Cailliet, G.M., Musick, J.A., Simpfendorfer, C.A., Stevens, J.D., 2005. Ecology and life history characteristics of chondrichthyan fish, in: Fowler, S.L., Cavanagh, R.D., Camhi, M., Burgess, G.H., Cailliet, G.M., Fordham, S.V., Simpfendorfer, C.A., Musick, J.A. (Eds.), Sharks, rays and chimaeras: the status of the chondrichthyan fishes, United Kingdom, pp. 461.

Carvalho, G.G.A., Degaspari, I.A.M., Branco, V., Canário, J., de Amorim, A.F., Kennedy, V.H., Ferreira, J.R., 2014. Assessment of total and organic mercury levels in blue sharks (*Prionace glauca*) from the south and southeastern Brazilian coast. Biol. Trace Elem. Res. 1591, 128-134. https://doi.org/10.1007/s12011-014-9995-6.

Cardoso, A.T.C., Vooren, C.M., 2010. Cintas plásticas e pesca fantasma em tubarões-azuis (*Prionace glauca*) e espadantes (*Xiphias gladius*) no Atlântico sudoeste. In III Congresso Brasileiro de Oceanografia–CBO, pp. 1155-1158.

Cascaes, M.J., Oliveira, R.T., Ubarana, M.M., Sato, R.M., Baldassin, P., Colabuono, F.I., Weber, R.R., 2014. Persistent organic pollutants in liver of Brazilian sharpnose shark (*Rhizoprionodon lalandii*) from southeastern coast of Brazil. Mar. Pollut. Bull. 86 , 591-593. https://doi.org/10.1016/j.marpolbul.2014.05.032.

Castro-Rendón, R.D., Calle-Morán, M.D., García-Arévalo, I., Ordiano-Flores, A., Galván-Magaña, F., 2022. Mercury and cadmium concentrations in muscle tissue of the blue shark

(*Prionace glauca*) in the central eastern Pacific Ocean. Biol. Trace Elem. Res. 200, 3400-3411. https://doi.org/10.1007/s12011-021-02932-7.

Chierichetti, M.A., Scenna, L.B., Ondarza, P.M., Giorgini, M., Di Giácomo, E., Miglioranza, K.S., 2021. Persistent organic pollutants and chlorpyrifos in the cockfish *Callorhinchus callorynchus* (Holocephali: Callorhynchidae) from Argentine coastal waters: Influence of sex and maturity. Sci. Total Environ. 796, 148-761. https://doi.org/10.1016/j.scitotenv.2021.148761.

Coelho, A.V., dos Santos Cunha, D.A., Freitas, J., Costa, J.F., dos Santos, E.C.B., Viana, D.C., 2020. Enriched cereal bar with ray meat *Hypanus guttatus* (Dasyatidae—Myliobatiformes) captured on Maranhão state coastal. Revista Gest. Sust. Am. 9, 525–535. https://doi.org/10.19177/rgsa.v9e02020525-535.

Compagno, L.J., 1990. Alternative life-history styles of cartilaginous fishes in time and space. Environ. Biol. Fishes 28, 33-75. https://doi.org/10.1007/BF00751027.

Concha, F.J., Caira, J.N., Ebert, D.A., Pompert, J.H.W., 2019. Redescription and taxonomic status of *Dipturus chilensis* (Guichenot, 1848), and description of *Dipturus lamillai* sp. nov. (Rajiformes: Rajidae), a new species of long-snout skate from the Falkland Islands. Zootaxa 4590, 501-524. https://doi.org/10.11646/zootaxa.4590.5.1.

Consales, G., Marsili, L., 2021. Assessment of the conservation status of Chondrichthyans: underestimation of the pollution threat. The Eur. Zool. J. 88, 165-180. https://doi.org/10.1080/24750263.2020.1858981.

Cordero-Maldonado, C., Espinoza, P., 2022. Cadmium and lead levels in muscle tissue of blue shark (*Prionace glauca*) in the Southeastern Pacific Waters. Mar. Pollut. Bull. 177, 113-523. https://doi.org/10.1016/j.marpolbul.2022.113523.

Corrêa, B., Paiva, L.G., Santos-Neto, E., Vidal, L.G., Azevedo-Silva, C.E., Vianna, M., Lailson-Brito, J.L., 2022. Organochlorine contaminants in Rio skate (*Rioraja agassizii*), an endangered batoid species, from the southeastern coast of Brazil. Mar. Pollut. Bull. 182, 114002. https://doi.org/10.1016/j.marpolbul.2022.114002.

De Boeck, G., Grosell, M., Wood, C., 2001. Sensitivity of the spiny dogfish (*Squalus acanthias*) to waterborne silver exposure. Aquat. Toxicol. 54, 261–275. https://doi.org/10.1016/S0166-445X(00)00180-6.

De Boeck, G., Hattink, J., Franklin, N.M., Bucking, C.P., Wood, S., Walsh, P.J., Wood, C.M., 2007. Copper toxicity in the spiny dogfish (Squalus acanthias): urea loss contributes to the osmoregulatory disturbance. Aquat. Toxicol. 84, 133–141. https://doi.org/10.1016/j.aquatox.2007.04.012.

Delgado, R.C., de Santana, R.O., Gelsleichter, Y.A., Pereira, M.G., 2022. Degradation of South American biomes: What to expect for the future?. Environ. Impact Assess. Rev. 96, 106815. https://doi.org/10.1016/j.eiar.2022.106815.

Di Giacomo, E.E., Perier, M.R., 1996. Feeding habits of cockfish, *Callorhinchus callorhynchus* (Holocephali: Callorhynchidae), in Patagonian waters (Argentina). Mar. Freshw. Res. 47, 801-808. https://doi.org/10.1071/MF9960801.

Dong, L., Zhang, L., Peng, Z., Guo, J., Zhang, X., Zhou, L., Huang, Y., 2022. Monitoring and ecological risk assessment of contaminants in freshwater bodies by bioindicators in China: a proposed framework. Environ. Sci. Pollut. Res. 1-12. https://doi.org/10.1007/s11356-022-21223-9.

Dulvy, N.K., Fowler, S.L., Musick, J.A., Cavanagh, R.D., Kyne, P.M., Harrison, L.R., Carlson, J.K., Davidson, L.N.k, Fordham, S.V., Francis, M.P., Pollock, C.M., Simpfendorfer, C.A., Burgess, G.H., Carpenter, K.E., Compagno, L.J., Ebert, D.A., Gibson, C., Heupel, M.R., Livingstone, S.R., Sanciangco, J.C., Stevens, J.D., Valenti, S., White, W.T., 2014. Extinction risk and conservation of the world's sharks and rays. Elife 3. https://doi.org/10.7554/eLife.00590.

Dulvy, N.K., Pacoureau, N., Rigby, C.L., Pollom, R.A., Jabado, R.W., Ebert, D.A., Simpfendorfer, C.A., 2021. Overfishing drives over one-third of all sharks and rays toward a global extinction crisis. Curr. Biol. 31,4773-4787. https://doi.org/10.1016/j.cub.2021.08.062.

Dwivedi, J., Trombetta, L.D., 2006. Acute toxicity and bioaccumulation of tributyltin in tissues of *Urolophus jamaicensis* (yellow stingray). J. Toxicol. Environ. Health Part A. 69, 1311-1323. https://doi.org/10.1080/15287390500356800.

Ebert, D.A., Fowler, S., Compagno, L., 2013. Sharks of the World. A Complete Guide. Wild Nature Press, United Kingdom, pp.608.

FAO, WHO. 2011. Safety evaluation of certain contaminants in food. Prepared by the sixty-fourth meeting of the joint FAO/WHO expert committee on food additives (JECFA). FAO Food Nutr. pp. 1–778.

Fernandez, C., Anastasopoulou, A., 2019. Plastic ingestion by blue shark *Prionace glauca* in the South Pacific Ocean (south of the Peruvian Sea). Mar. Pollut. Bull. 149, 110501. https://doi.org/10.1016/j.marpolbul.2019.110501.

Ferretti, F., Worm, B., Britten, G.L., Heithaus, M.R., Lotze, H.K., 2010. Patterns and ecosystem consequences of shark declines in the ocean. Ecol. Lett. 13, 1055-1071. https://doi.org/10.1111/j.1461-0248.2010.01489.x.

Fields, A.T., Fischer, G.A., Shea, S.K.H., Zhang, H., Abercrombie, D.L., Feldheim, K.A., Babcock, E.A., Chapman, D.D., 2017. Species composition of the international shark fin trade assessed through retail-market survey in Hong Kong. Conserv. Biol. 32, 376–389. https://doi.org/10.1111/cobi.13043.

Fuentes-Ríos, D., Orrego, R., Rudolph, A., Mendoza, G., Gavilán, J.F., Barra, R., 2005. EROD activity and biliary fluorescence in *Schroederichthys chilensis* (Guichenot 1848): Biomarkers of PAH exposure in coastal environments of the South Pacific Ocean. Chemosphere 61, 192-199. https://doi.org/10.1016/j.chemosphere.2005.02.062.

Gonzalez-Pestana, A., Alfaro-Shigueto, J., Mangel, J.C., Espinoza, P., 2017. Niveles de mercurio en el tiburón martillo *Sphyrna zygaena* (Carcharhiniformes: Sphyrnidae) del norte del Perú. Rev. Peru. Biol. 24, 407-411. http://dx.doi.org/10.15381/rpb.v24i4.14066.

Grijalba-Bendeck, M., Acero, A., Díaz-Trujillo, E.M., Gómez, F., 2009. Estado del conocimiento de los peces cartilaginosos del Caribe continental de Colombia, in: Puentes, V., Navia, A.F., Mejía Falla, P.A., Caldas, J.P., Diazgranados, M.C., Zapata Padilla, L.A. (Eds.), Avances en el conocimiento de tiburones, rayas y quimeras de Colombia, Colombia, pp. 38-96.

Hauser-Davis, R.A., Pereira, C.F., Pinto, F., Torres, J.P.M., Malm, O., Vianna, M., 2020a. Mercury contamination in the recently described Brazilian white-tail dogfish *Squalus albicaudus* (Squalidae, Chondrichthyes). Chemosphere 250, 126228. http://dx.doi.org/10.1016/j.chemosphere.2020.126228.

Hauser-Davis, R.A., Barbosa-Filho, M.L., Pereira, L.H.S.D.S., Lopes, C.A., Moreira, S.C., Rocha, R.C., Siciliano, S., 2020b. First record of a morphologically abnormal and highly metal-contaminated Spotback Skate *Atlantoraja castelnaui* (Rajiformes: Arhynchobatidae) from southeastern Rio de Janeiro, Brazil. J. Threat. Taxa. 12, 16510-16520. http://dx.doi.org/10.11609/jott.5903.12.11.16510-16520.

Hauser-Davis, R.A., Monteiro, F., Willmer, I.Q., Lemos, L.S., Bordon, I.C., Saint'Pierre, T.D., Vianna, M., 2022. Subcellular metal partitioning as a novel tool in ecotoxicological elasmobranch assessments: The case of lesser numbfish (*Narcine brasiliensis*) affected by the Mariana dam disaster in Southeastern Brazil. Mar. Pollut. Bull. 177, 113569. https://doi.org/10.1016/j.marpolbul.2022.113569.

Incardona, J.P., Collier, T.K., Scholz, N.L., 2004. Defects in cardiac function precede morphological abnormalities in fish embryos exposed to polycyclic aromatic hydrocarbons. Toxicol. Appl. Pharmacol. 196, 191-205. https://doi.org/10.1016/j.taap.2003.11.026.

Instituto Nacional de Desarrollo Pesquero (INIDEP). 2018. Pez gallo. Mar del Plata, Argentina Available at: http://inidep.edu.ar/investigacion/pesquerias/especies/52-pez-gallo.html.

Julio, T.G., Moura, V.L., Lacerda, L.D., Lessa, R., 2022. Mercury concentrations in coastal Elasmobranchs (*Hypanus guttatus* and *Rhizoprionodon porosus*) and human exposure in Pernambuco, Northeastern Brazil. Anais Acad. Brasil. Ci. 94. https://doi.org/10.1590/0001-3765202220220045.

Kibria, G., Nugegoda, D., Haroon, A.Y., 2022. Microplastic pollution and contamination of seafood (including fish, sharks, mussels, oysters, shrimps and seaweeds): A Global overview, in: Muhammad, Z.H. (Ed.), Microplastic Pollution: Environmental Occurrence and Treatment Technologies, Pakistan, pp. 277-322.

Lacerda, L.D., Paraquetti, H.H.M., Marins, R.V., Rezende, C.E., Zalmon, I.R., Gomes, M.P., Farias, V., 2000. Mercury content in shark species from the south-eastern Brazilian coast. Revista Brasil. Biol. 60, 571-576. https://doi.org/10.1590/S0034-71082000000400005.

La Colla, N.S., Botté, S.E., Marcovecchio, J.E., 2018. Metals in coastal zones impacted with urban and industrial wastes: Insights on the metal accumulation pattern in fish species. J. Mar. Syst. 181, 53-62. https://doi.org/10.1016/j.jmarsys.2018.01.012.

La Colla, N.S., Botté, S.E., Simonetti, P., Negrin, V.L., Serra, A.V., Marcovecchio, J.E., 2021. Water sediments and fishes: First multi compartment assessment of metal pollution in a coastal environment from the SW Atlantic. Chemosphere 282, 131131. https://doi.org/10.1016/j.chemosphere.2021.131131.

Lara-Martín, P.A., Gómez-Parra, A., Petrovic, M., Barceló, D., González-Mazo, E., 2005. Distribution of organic pollutants in coastal sediments of Cádiz Bay (SW Spain). Cienc. Mar. 31, 203-212. https://doi.org/10.7773/cm.v31i12.95.

Last, P.R., Stevens, J.D., 2009. Sharks and rays of Australia, in: Last, P.R., Stevens, J.D. (Eds.), CSIRO, Australia, pp.656

Last, P., White, W., de Carvalho, M., Séret, B., Stehmann, M., Naylor, G., 2016. Rays of the World, in: CSIRO Publishing, Comstock Publishing Associates, Clayton, pp.1-790.

Logan, D.T., 2007. Perspective on ecotoxicology of PAHs to fish. Hum. Ecol. Risk Assess. 13, 302-316. https://doi.org/10.1080/10807030701226749.

Lopez, S., Barría, P., Meléndez, R., 2012. Scientific Note Feeding and trophic relationships of two highly migratory sharks in the eastern south Pacific Ocean. Pan-Am. J. of Aquat. Sci. 7, 50-56.

Lopez, S.A., Abarca, N.L., Meléndez, R.C., 2013. Heavy metal concentrations of two highly migratory sharks (*Prionace glauca* and *Isurus oxyrinchus*) in the southeastern Pacific waters: comments on public health and conservation. Trop. Conserv. Sci. 6, 126-137. https://doi.org/10.1177/194008291300600103.

Lucifora, L.O., de Carvalho, M.R., Kyne, P.M., White, W.T., 2015. Freshwater sharks and rays. Curr. Biol. 25, R971-R973. https://doi.org/10.1016/j.cub.2015.06.051.

Lyons, K., Carlisle, A., Preti, A., Mull, C., Blasius, M., O'Sullivan, J., Lowe, C.G., 2013. Effects of trophic ecology and habitat use on maternal transfer of contaminants in four species of young of the year lamniform sharks. Mar. Environ. Res. 90, 27-38. https://doi.org/10.1016/j.marenvres.2013.05.009.

Lyons, K., Lavado, R., Schlenk, D., Lowe, C.G., 2014. Bioaccumulation of organochlorine contaminants and ethoxyresorufin-o-deethylase activity in southern California round stingrays (Urobatis halleri) exposed to planar aromatic compounds. Environ. Toxicol. Chem. 33, 1380–1390. https://doi.org/10.1002/etc.2564.

Marcovecchio, J.E., Moreno, V.J., Pérez, A., 1991. Metal accumulation in tissues of sharks from the Bahía Blanca estuary, Argentina. Mar. Environ. Res. 31, 263-274. https://doi.org/10.1016/0141-1136(91)90016-2.

Martins, M.F., Costa, P.G., Bianchini, A., 2020. Contaminant screening and tissue distribution in the critically endangered Brazilian guitarfish *Pseudobatos horkelii*. Environ. Pollut. 265, 114923. https://doi.org/10.1016/j.envpol.2020.114923.

Martins, M.F., Costa, P.G., Bianchini, A., 2021a. Maternal transfer of polycyclic aromatic hydrocarbons in an endangered elasmobranch, the Brazilian guitarfish. Chemosphere 263, 128275. https://doi.org/10.1016/j.chemosphere.2020.128275.

Martins, M.F., Costa, P.G., Bianchini, A., 2022a. Assessing multigenerational exposure to metals in elasmobranchs: Maternal transfer of contaminants in a yolk-sac viviparous species. Mar. Pollut. Bull. 175, 113364. https://doi.org/10.1016/j.marpolbul.2022.113364.

Maurice, L., Le Croizier, G., Morales, G., Carpintero, N., Guayasamin, J.M., Sonke, J., Ochoa-Herrera, V., 2021. Concentrations and stable isotopes of mercury in sharks of the Galapagos Marine Reserve: Human health concerns and feeding patterns. Ecotoxicol. Environ. Saf. 215, 112122. https://doi.org/10.1016/j.ecoenv.2021.112122.

Menni, R., Stehmann, M., 2000. Distribution, environment and biology of batoid fishes off Argentina, Uruguay and Brazil. A review. Rev. Mus. Arg. Cienc. Nat. Nueva Ser. 2, 69-109.

Miranda, D.D.A., de Carvalho-Souza, G.F., 2016. Are we eating plastic-ingesting fish?. Mar. Pollut. Bull. 103, 109-114. https://doi.org/10.1016/j.marpolbul.2015.12.035.

Mittermeier, R.A., Goettsch Mittermeier, C., Robles Gil, P., Wilson, E.O., 1997. Megadiversity: earth's biologically wealthiest nations (First English). CEMEX.

Moura, V.L., Rabelo, J.N., Bezerra, M.F., da Silva, G.B., Faria, V.V., Rezende, C.E., de Lacerda, L.D., 2020. Ecological and biological factors associated to mercury accumulation in batoids (Chondrichthyes: Batoidea) from northeastern Brazil. Mar. Pollut. Bull. 161, 111761. https://doi.org/10.1016/j.marpolbul.2020.111761.

Mull, C.G., Blasius, M.E., O'Sullivan, J.B., Lowe, C.G., 2012. Heavy metals, trace elements, and organochlorine contaminants in muscle and liver tissue of juvenile white sharks, *Carcharodon carcharias*, from the Southern California Bight, in: Domeier, M.L. (Ed.), Global perspectives on the biology and life history of the white shark, Californy, pp. 75.

Oddone, M.C., Paesch, L., Norbis, V., 2005. Reproductive biology and seasonal distribution of *Mustelus schmitti* (Elasmobranchii: Triakidae) in the Rio de la Plata oceanic front, south-western Atlantic. J. Mar. Biolog. Assoc. 1193-1198.

Oliva, A.L., La Colla, N.S., Arias, A.H., Blasina, G.E., Lopez Cazorla, A., Marcovecchio, J.E., 2017. Distribution and human health risk assessment of PAHs in four fish species from a SW Atlantic estuary. Environ. Sci. Pollut. Res. 24, 18979-18990. https://doi.org/10.1007/s11356-017-9394-6.

Oliva, A.L., Girones, L., Recabarren-Villalón, T.V., Ronda, A.C., Marcovecchio, J.E., Arias, A.H., 2022. Occurrence, behavior and the associated health risk of organochlorine pesticides in sediments and fish from Bahía Blanca Estuary, Argentina. Mar. Pollut. Bull. 185, 114247. https://doi.org/10.1016/j.marpolbul.2022.114247.

Pegado, K., Winemiller, K.O., Chelazzi, D., Cincinelli, A., Dei, L., Giarrizzo, T., 2018. First evidence of microplastic ingestion by fishes from the Amazon River estuary. Mar. Pollut. Bull. 133, 814-821. https://doi.org/10.1016/j.marpolbul.2018.06.035.

Pegado, T., Brabo, L., Schmid, K., Sarti, F., Gava, T.T., Nunes, J., Giarrizzo, T., 2021. Ingestion of microplastics by *Hypanus guttatus* stingrays in the Western Atlantic Ocean (Brazilian Amazon Coast). Mar. Pollut. Bull. 162, 111799. https://doi.org/10.1016/j.marpolbul.2020.111799.

Penedo de Pinho, A.P., Guimarães, J.R.D., Martins, A.S., Costa, P.A.S., Olavo, G., Valentin, J., 2002. Total mercury in muscle tissue of five shark species from Brazilian offshore waters: effects of feeding habit, sex, and length. Environ. Res. 89, 250-258. https://doi.org/10.1006/enrs.2002.4365.

Pimienta, V.T.A., Ferreira I.A., De Castro Rodrigues, A.P., De Albuquerde, C., Castilho, Z.C., Line, A.R., 2005. Mercury and metallothionein levels in shark species from Southeastern

Brazil, in: Proceedings of the XIII International Conference on Heavy Metals in the Environment, pp. 59.

Provenza, F., Rampih, D., Pignattelli, S., Pastorino, P., Barceló, D., Prearo, M., Renzi, M., 2022. Mussel watch program for microplastics in the Mediterranean sea: Identification of biomarkers of exposure using *Mytilus galloprovincialis*. Ecol. Indic. 142, 109212. https://doi.org/10.1016/j.ecolind.2022.109212.

Reátegui-Quispe, A., Pariona-Velarde, D., 2019. Determinación de plomo, cadmio, mercurio y Bases Volátiles Nitrogenadas Totales (NBVT) en el músculo de tiburón azul *Prionace glauca* procedente de la zona sur del Perú. Rev. Biol. Mar. Oceanogr. 54, 336-342. http://dx.doi.org/10.22370/rbmo.2019.54.3.2029.

Recabarren-Villalón, T., Ronda, A.C., Oliva, A.L., Cazorla, A.L., Marcovecchio, J.E., Arias, A.H., 2021. Seasonal distribution pattern and bioaccumulation of Polycyclic aromatic hydrocarbons (PAHs) in four bioindicator coastal fishes of Argentina. Environ. Pollut. 291, 118125. http://dx.doi.org/10.1016/j.envpol.2021.118125.

Sazima, I., Gadig, O.B., Namora, R.C., & Motta, F.S., 2002. Plastic debris collars on juvenile carcharhinid sharks (*Rhizoprionodon lalandii*) in southwest Atlantic. Mar. Pollut. Bull. 44, 1149-1151. https://doi.org/10.1016/s0025-326x(02)00141-8.

Segura, A.M., Milessi, A.C., 2009. Biological and reproductive characteristics of the Patagonian smoothhound *Mustelus schmitti* (Chondrichthyes, Triakidae) as documented from an artisanal fishery in Uruguay. J. Appl. Ichthyol. 25, 78-82. https://doi.org/10.1111/j.1439-0426.2009.01250.x.

Souza-Araujo, J., Andrades, R., de Oliveira Lima, M., Hussey, N.E., Giarrizzo, T., 2020. Maternal and embryonic trace element concentrations and stable isotope fractionation in the smalleye smooth-hound (*Mustelus higmani*). Chemosphere 257, 127183. https://doi.org/10.1016/j.chemosphere.2020.127183.

Stankovic, S., Kalaba, P., Stankovic, A.R., 2014. Biota as toxic metal indicators. Environ. Chem. Lett. 12, 63-84. https://doi.org/10.1007/s10311-013-0430-6.

Stevens, J.D., Bonfil, R., Dulvy, K., Walker, P.A., 2000. The effects of fishing on sharks, rays and chimaeras (chondrichthyans) and the implications for marine ecosystems. ICES J. Mar. Sci. 57, 476-494. https://doi.org/10.1006/jmsc.2000.0724.

Subsecretaría de Pesca y Acuicultura (SUBPESCA). 2018. Pejegallo. Valparaíso, Chile Available at: http://www.subpesca.cl/portal/616/w3-article-837.html.

Suedel, B.C., Boraczek, J.A., Peddicord, R.K., Clifford, P.A., Dillon, T.M., 1994. Trophic transfer and biomagnification potential of contaminants in aquatic ecosystems. Rev. Environ. Contam. Toxicol. 21–89. https://doi.org/10.1007/978-1-4612-2656-7_2.

Tagliafico, A., Rago, N., Barany, M., Rangel, S., 2015. Biología de Rhizoprionodon lalandii (Elasmobranchii: Carcharhinidae) capturado en la pesca artesanal de Isla de Margarita, Venezuela. Rev. Biol. Trop. 63, 1091-1103.

Tiktak, G.P., Butcher, D., Lawrence, P.J., Norrey, J., Bradley, L., Shaw, K., Megson, D., 2020. Are concentrations of pollutants in sharks, rays and skates (Elasmobranchii) a cause for concern? A systematic review. Mar. Pollut. Bull. 160, 111701. https://doi.org/10.1016/j.marpolbul.2020.111701.

UNEP (United Nations Environment Programme), 2002a. Regionally based assessment of persistent toxic substances - Eastern and Western South America. Regional Report.

Unión Europea. Reglamento (CE) Nº 1881/2006 de 19 de diciembre de 2006 por el que se fija el contenido máximo de determinados contaminantes en los productos alimenticios. Diario Oficial de la Unión Europea, 19 de diciembre 2006.

USEPA, 2000. Fish Sampling and Analysis. EPA 823-B-00-007. Guidance for Assessing Chemical Contaminant Data for Use in Fish Advisories, vol. 1. Office of Science and Technology Office of Water U.S. Environmental Protection Agency, Washington, DC.

Van der Oost, R., Beyer, J., Vermeulen, N.P., 2003. Fish bioaccumulation and biomarkers in environmental risk assessment: a review. Environ. Toxicol. Pharmacol. 13, 57-149. https://doi.org/10.1016/s1382-6689(02)00126-6.

Venerus, L.A., Cedrola, P.V., 2017. Review of marine recreational fisheries regulations in Argentina. Mar. Policy 81, 202-210. https://doi.org/10.1016/j.marpol.2017.03.007.

Willmer, I.Q., Wosnick, N., Rocha, R.C.C., Saint'Pierre, T.D., Vianna, M., Hauser-Davis, R.A., 2022. First report on metal and metalloid contamination of Ampullae of Lorenzini in sharks: A case study employing the Brazilian sharpnose shark *Rhizoprionodon lalandii* from Southeastern Brazil as an ecotoxicological model. Mar. Pollut. Bull. 179, 113671. https://doi.org/10.1016/j.marpolbul.2022.113671.

Wosnick, N., Niella, Y., Hammerschlag, N., Chaves, A.P., Hauser-Davis, R.A., da Rocha, R.C.C., Nunes, J.L.S., 2021a. Negative metal bioaccumulation impacts on systemic shark health and homeostatic balance. Mar. Pollution Bull. 168, 112398. https://doi.org/10.1016/j.marpolbul.2021.112398.

Wosnick, N., Chaves, A.P., Leite, R.D., Nunes, J.L.S., Saint'Pierre, T.D., Willmer, I.Q., Hauser-Davis, R.A., 2021b. Nurse sharks, space rockets and cargo ships: Metals and oxidative stress in a benthic, resident and large-sized mesopredator, *Ginglymostoma cirratum*. Environ. Pollut. 288, 117784. https://doi.org/10.1016/j.envpol.2021.117784.

Yao, P., Zhou, B., Lu, Y., Yin, Y., Zong, Y., Chen, M.T., O'Donnell, Z., 2019. A review of microplastics in sediments: Spatial and temporal occurrences, biological effects, and analytic methods. Quat. Int. 519, 274-281. https://doi.org/10.1016/j.quaint.2019.03.028.

Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: