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Assessment of the conservation status of Chondrichthyans: underestimation of the pollution threat

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Abstract
Cartilaginous fish include sharks, rays, skates, sawfish, and chimaeras. Their habitat ranges from shallow coastal waters to deep ocean floors, estuarine areas as well as rivers and inland waters. Overfishing is considered to be the main threat to their existence, but there are many more stressors that these species face. Pollution is an issue that concerns aquatic organisms at every level, and Chondrichthyans are no exception. Here, we looked at their IUCN Red List assessment, and noticed a lack of information regarding anthropogenic contamination for these species. Out of 1124 cartilaginous fish species assessed, only 17 *Selachimorpha* and 32 *Batoidea* species were considered to be facing a "pollution threat"; in most cases, the threat was assigned not from direct ecotoxicological studies of the specimens, but because the species inhabited areas likely to be contaminated. An update on the conservation status of these species is urgently needed. Further, there is a fundamental need to study the effects of contaminants on Chondrichthyans as they play a key role in aquatic ecosystems.

Keywords: *Chondrichthyans, pollution, conservation, IUCN Red List, persistent organic pollutants*

Introduction

There are 1200 species of Chondrichthyans, the majority of which inhabit marine ecosystems (Weigmann 2016). Sharks, rays, skates, sawfish, and chimaeras belong to this class. Chondrichthyans also occupy a large range of habitats, from shallow coastal waters to deep-sea floors. For this reason, they are subjected to many different threats and stressors. To date, the most prominent threat to cartilaginous fish is overfishing (Dulvy et al. 2014). Since the introduction of large-scale commercial fishing, sharks and rays have been caught indiscriminately in large quantities, despite not being the primary targets of fisheries. More recently, however, developing markets and depleting numbers of traditionally commercial fish have made these "bycatch" sharks and rays increasingly desirable. Sharks and rays are also intentionally caught and killed because of the perceived threat they pose to humans as well as the incessant demand for shark products, including liver oil, fins, and gills (Fowler et al. 2002; Clarke et al. 2006; Lack & Sant 2009). Habitat depletion and environmental contamination also represent substantial dangers to Chondrichthyans. A large portion (~71%) of the Earth's surface is covered with water, and until the 1970s, most toxic wastes were discarded in the oceans (Lumsdaine 1975) with little understanding of the true negative impacts of such actions. The most common assumption was that the ocean had an unlimited capacity to mix and disperse debris and substances; therefore, after years of uncontrolled dumping, the first effects began to emerge in the 1980s (Lear et al. 1981; Messieh et al. 1991). This led to conventions and international agreements for the protection of the marine environment from human activities and for the production, use, and disposal of toxic substances (Craig 2004). The effects of chemicals, especially persistent organic pollutants (*POPs*), are well known and have been studied in many marine species (Fossi et al. 2013; Marsili et al. 2014; Brown & Takada 2017; Casini et al. 2018; Mearns et al. 2019; Righetti et al. 2019; Quintanilla-

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Mena et al. 2020). *POPs* interfere with organisms, compromising multiple physiological processes; they have immunosuppressive properties, are carcinogenic, mutagenic, and teratogenic, and some are known to be endocrine disruptors (Jimenez 1997; Matthiessen 2003; Mikula & Svobodova 2006; IARC Working Group on the Evaluation of Carcinogenic Risks to Humans 2016; Centelleghe et al. 2019; Marsili et al. 2019). Even naturally occurring contaminants such as PAHs and heavy metals, which have been made more bioavailable by human activities, are known to be important stress factors for marine organisms (Marsili et al. 2014, 2016; Scheuhammer et al. 2015; Santana et al. 2018; Cunningham et al. 2019; Lee et al. 2019). Furthermore, most studies have demonstrated the existence of pollutants in Chondrichthyans and their environments (Gelsleichter & Walker 2010), but few have examined the impact and effects of chemicals on these organisms (Fuentes-Rios et al. 2005; Solé et al. 2010a, 2010b; Barrera-García et al. 2012, 2013; Vélez-Alavez et al. 2013; Alves et al. 2016; Marsili et al. 2016; Fossi et al. 2017; Cullen et al. 2019; Lyons & Wynne-Edwards 2019; Ehnert-Russo & Gelsleichter 2020).

However, environmental contamination is the least studied of the aforementioned threats and stressors, as confirmed by the number of scientific papers on pollution in elasmobranchs. A research conducted on three of the foremost online databases (Scopus, Web of Science, and PubMed) revealed that only approximately 4% of published papers on Chondrichthyes discuss contamination. The research was conducted using keywords such as *"Chondrichthyes"*, *"elasmobranchs"*, *"sharks"*, *"batoids"*, *"contaminants"*, *"organochlorines"*, *"pesticides"*, *"pollution"*, *"plastic"*, *"polychlorobiphenyls (PCBs)"*, *"Polybrominated diphenyl ethers (PBDEs)"*, *"Dichlorodiphenyltrichloroethane (DDT)"*, *"Polycyclic aromatic hydrocarbons (PAHs)"*, *"Phthalates"*, *"Bisphenol A (BPA)"*, *"heavy metals,"*, and *"mercury"* together, in different combinations, or separately to refine results.

The principal aim of this study was to highlight the lack of information regarding pollution in cartilaginous fish, which play a key role in aquatic ecosystems. We reviewed data available from the International Union for Conservation of Nature (IUCN) Red List of Threatened Species, the main database on the conservation status of biological species. Using the "*advanced search*" tool in the IUCN Red List website, which helps to filter data based on multiple categories (species, regions, documents, and Red List Indices), we identified a way to extrapolate information on Chondrichthyes assessed for pollution. In particular, in the section "*Taxonomy*", we ticked the box "*Chondrichthyes*", and in the section "*Threats*", we ticked the box "*Pollution*". With this first step, we want to fill the gap in knowledge regarding publications on the effect of pollutants in Chondrichthyes and the assessment of cartilaginous fish in the IUCN Red List.

Results

The IUCN Red List states that 30% of Chondrichthyans are threatened by extinction; however, "pollution" is mentioned in the threat assessment of only 4%. During species assessment, a scheme must be followed to assign a specific threat to a species, available on the IUCN Red List website. Appendix 1 reports an extract from the IUCN Unified Classification of Direct Threats, mainly focused on the Pollution threat. This scheme suggests six pollution classes; the first four are known for affecting aquatic organisms in general, the fifth involves airborne pollutants, and the last refers to inputs of heat, sound, or light that disturb wildlife or ecosystems. As most of the chemicals that were used and continue to be used by humans unfortunately end up in aquatic ecosystems, it seems logical that at least one pollution class be assigned to Chondrichthyans. After a thorough search on the IUCN Red List website, we found that out of 1124 cartilaginous fish species, only 17 *Selachimorpha* and 32 *Batoidea* species were assigned the "pollution threat". Table I and II list these species with their scientific names, IUCN classification status, assigned pollution class, and last assessment date.

After evaluating the information provided by IUCN, it has emerged that the species present in Table I have a fairly limited range; they are not cosmopolitan species but are often endemic. In some cases, the pollution category has been assigned to species that are barely known and studied, such as the New Caledonia Catshark. In fact, this species is known from only one caught specimen and two photographs (Seret 1990; Ebert et al. 2013; Finucci & Kyne 2018). In most cases, the pollution threat is assigned to the species because they inhabit an area that is known to be, or might be, stressed from anthropogenic factors. Mostly, there is no mention of either the studies conducted in the area or the potential contamination sources. The only ecotoxicological study conducted on the listed species and mentioned in the assessment is the one by Al-Hassan et al. (2000), who investigated the presence of PAHs in *Chiloscyllium arabicum*. To verify whether there were other studies on contamination in these species, we searched for literature regarding pollution for each of the shark species listed in Table

Table I. Species, common name, IUCN Red List classification status, assigned pollution threat, and last assessment date.

Selachimorpha

Species	Common name	IUCN Red List status	Pollution threat	Last assessed
Aulohalaelurus kanakorum	New Caledonia Catshark	Data Deficient (DD)	9.2.2. Seepage from mining	20 June 2017
Carcharhinus leiodon	Smoothtooth Blacktip Shark	Endangered (EN)	9.2.1. Oil spills	09 February 2017
Chiloscyllium arabicum	Arabian Carpetshark	Near Threatened (NT)	9.1.2. Run-off 9.2.1. Oil spills	09 February 2017
Glyphis glyphis	Speartooth Shark	Endangered (EN)	9.2.2. Seepage from mining	01 October 2005
Glyphis siamensis	Irrawaddy River Shark	Critically Endangered (CR)	9.1.3. Type Unknown/Unrecorded 9.3.2. Soil erosion, sedimentation 9.3.4. Type Unknown/Unrecorded	01 December 2008
Haploblepharus edwardsii	Puffadder Shyshark	Near Threatened (NT)	9.1.3. Type Unknown/Unrecorded	01 December 2008
Haploblepharus fuscus	Brown Shyshark	Vulnerable (VU)	9.1.3. Type Unknown/Unrecorded	01 December 2008
Haploblepharus kistnasamyi	Natal Shyshark	Vulnerable (VU)	9.1.3. Type Unknown/Unrecorded	25 April 2018
Hemiscyllium hallstromi	Papuan Epaulette Shark	Vulnerable (VU)	9.1.1. Sewage 9.2.2. Seepage from mining	18 February 2015
Hemiscyllium michaeli	Michael's Epaulette Shark	Near Threatened (NT)	9.3.2. Soil erosion, sedimentation	24 January 2012
Hemiscyllium strahani	Hooded Carpetshark	Vulnerable (VU)	9.2.2. Seepage from mining	30 April 2003
Nasolamia velox	Whitenose Shark	Data Deficient (DD)	9.3.2. Soil erosion, sedimentation	01 December 2008
Paragaleus randalli	Slender Weasel Shark	Near Threatened (NT)	9.2.1. Oil spills	01 December 2008
Poroderma pantherinum	Leopard Catshark	Data Deficient (DD)	9.1.3. Type Unknown/Unrecorded	12 May 2004
Rhizoprionodon lalandii	Brazilian Sharpnose Shark	Data Deficient (DD)	9.4. Garbage and solid waste	30 April 2004
Rhizoprionodon longurio	Pacific Sharpnose Shark	Data Deficient (DD)	9.1.3. Type Unknown/Unrecorded	01 December 2008
Schroederichthys tenuis	Slender Catshark	Data Deficient (DD)	9.2.3. Type Unknown/Unrecorded 9.3.3. Herbicides and pesticides	30 April 2004

Table II. Species, common name, IUCN Red List classification status, assigned pollution threat, and last assessment date.

Batoidea

Species	Common name	IUCN Red List status	Pollution threat	Last assessed
Anoxypristis cuspidata	Narrow Sawfish	Endangered (EN)	9.1.1. Sewage 9.1.2. Run-off 9.2.1. Oil spills 9.2.2. Seepage from mining 9.3.1. Nutrient loads 9.3.2. Soil erosion, sedimentation 9.3.3. Herbicides and pesticides	07 April 2012
Brevitrygon imbricata	Scaly Whipray	Data Deficient (DD)	9.2.3. Type Unknown/Unrecorded	08 September 2004
Brevitrygon walga	Scaly Whipray	Near Threatened (NT)	9.2.1. Oil spills	09 February 2017
Fluvitrygon kittipongi		Endangered (EN)	9.1.3. Type Unknown/Unrecorded 9.3.3. Herbicides and pesticides	11 July 2007
Fluvitrygon oxyrhyncha	Longnose Marbled Whipray	Endangered (EN)	9.1.1. Sewage 9.2.3. Type Unknown/Unrecorded 9.3.3. Herbicides and pesticides 9.3.2. Soil erosion, sedimentation	03 October 2005
Fluvitrygon signifer	White-edge Freshwater Whipray	Endangered (EN)	9.1.1. Sewage 9.2.3. Type Unknown/Unrecorded 9.3.3. Herbicides and pesticides	03 October 2005
Gymnura crebripunctata	Mazatlan Butterfly Ray	Data Deficient (DD)	9.1.1. Sewage 9.1.2. Run-off	30 April 2011
Gymnura marmorata	California Butterfly Ray	Least Concern (LC)	9.1.1. Sewage 9.1.2. Run-off	30 April 2011
Hemitrygon fluviorum	Estuary Stingray	Vulnerable (VU)	9.2.2. Seepage from mining	02 May 2003
Hemitrygon laevigata	Yantai Stingray	Near Threatened (NT)	9.1.3. Type Unknown/Unrecorded	03 December 2008
Himantura undulata	Bleeker's Variegated Whipray	Vulnerable (VU)	9.1.3. Type Unknown/Unrecorded 9.3.1. Nutrient loads 9.3.2. Soil erosion, sedimentation	12 December 2011
Maculabatis pastinacoides	Round Whipray	Vulnerable (VU)	9.2.2. Seepage from mining	12 September 2004
Maculabatis randalli	Arabian Banded Whipray	Least Concern (LC)	9.2.1. Oil spills	08 February 2017
Mobula birostris	Giant Manta Ray	Vulnerable (VU)	9.1.1. Sewage 9.1.2. Run-off	01 November 2010
Narcine atzi	Oman Numbfish	Data Deficient (DD)	9.1.3. Type Unknown/Unrecorded	12 September 2004
Narcine lingula	Chinese Numbfish	Data Deficient (DD)	9.3.2. Soil erosion, sedimentation	01 January 2007
Pastinachus solocirostris	Roughnose Stingray	Endangered (EN)	9.1.3. Type Unknown/Unrecorded	08 July 2007
Plesiotrygon iwamae	Antenna Ray	Data Deficient (DD)	9.1.1. Sewage 9.2.2. Seepage from mining 9.3.2. Soil erosion, sedimentation	24 June 2003
Potamotrygon brachyura	Giant Freshwater Stingray	Data Deficient (DD)	9.3.3. Herbicides and pesticides	24 June 2003
Potamotrygon castexi	Vermiculate River Stingray	Data Deficient (DD)	9.3.1. Nutrient loads	24 June 2003

(*Continued*)

Table II. (Continued).

Batoidea

Species	Common name	IUCN Red List status	Pollution threat	Last assessed
Potamotrygon leopoldi	Xingu River Ray	Data Deficient (DD)	9.1.1. Sewage 9.3.2. Soil erosion, sedimentation 9.3.4. Type Unknown/Unrecorded	24 June 2003
Potamotrygon magdalenae	Magdalena Freshwater Stingray	Least Concern (LC)	9.1.2. Run-off 9.3.4. Type Unknown/Unrecorded	08 October 2014
Potamotrygon scobina	Raspy River Stingray	Data Deficient (DD)	9.2.2. Seepage from mining 9.3.3. Herbicides and pesticides	30 April 2004
Potamotrygon yepezi	Maracaibo River Stingray	Data Deficient (DD)	9.3.4. Type Unknown/Unrecorded	05 May 2004
Pristis clavata	Dwarf Sawfish	Endangered (EN)	9.2.2. Seepage from mining 9.2.1. Oil spills	07 May 2012
Pristis pristis	Largetooth Sawfish	Critically Endangered (CR)	9.3.1. Nutrient loads 9.3.2. Soil erosion, sedimentation	01 March 2013
Pristis zijsron	Green Sawfish	Critically Endangered (CR)	9.3.1. Nutrient loads 9.3.2. Soil erosion, sedimentation	20 May 2012
Rhinobatos albomaculatus	White-spotted Guitarfish	Vulnerable (VU)	9.1.3. Type Unknown/Unrecorded 9.2.3. Type Unknown/Unrecorded 9.3.4. Type Unknown/Unrecorded	01 December 2008
Rhinobatos irvinei	Spineback Guitarfish	Vulnerable (VU)	9.1.3. Type Unknown/Unrecorded 9.2.3. Type Unknown/Unrecorded 9.3.4. Type Unknown/Unrecorded	01 December 2008
Torpedo mackayana	West African Torpedo Ray	Data Deficient (DD)	9.1.3. Type Unknown/Unrecorded 9.2.3. Type Unknown/Unrecorded 9.3.4. Type Unknown/Unrecorded	01 January 2007
Urogymnus polylepis	Giant Freshwater Stingray	Endangered (EN)	9.1.3. Type Unknown/Unrecorded 9.2.3. Type Unknown/Unrecorded 9.3.1. Nutrient loads 9.3.3. Herbicides and pesticides 9.3.2. Soil erosion, sedimentation	27 February 2011
Urotrygon nana	Dwarf Round Stingray	Data Deficient (DD)	9.1.1. Sewage 9.2.3 Type Unknown/Unrecorded 9.3.2. Soil erosion, sedimentation	01 December 2008

I and found that there were indeed three more species with documented presence of pollutants in their tissues and one more ecotoxicological study on *C. arabicum*. In this species, Adel et al. (2018) noted six different metals (cadmium (Cd), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb), and zinc (Zn)) in the liver and muscle of 40 specimens sampled from two sites. The presence of metals in both tissues and liver were higher in specimens collected in the area with more human activity. Adel et al. (2018) also performed a risk assessment for food intake; the risk for consumers was low for all the metals, with the exception of total mercury (THg), which was near the risk threshold upon high frequencies of consumption. However, even if the risk for consumers is low, there may still be a risk for the specimen and its physiological status.

The three other species on which ecotoxicological studies were conducted are the smoothtooth blacktip shark (*Carcharhinus leiodon*), the Brazilian sharpnose shark (*Rhizoprionodon lalandii*), and the Pacific sharpnose shark (*R. longurio*). Moore et al. (2015) demonstrated the presence of 11 trace elements in the muscles of five *C. leiodon* juveniles and two adult specimens in northern Kuwait waters. In particular, they looked for arsenic (As), Cd, chromium (Cr), Cu, iron (Fe), Hg, manganese (Mn), Ni, Pb, selenium (Se), and Zn and found that mercury concentrations were higher than the limits imposed by the European Food Safety Authority. The levels of other elements and contaminants may nevertheless act as further stressors to these species. Three papers have been published on Brazilian sharpnose sharks, in which the presence of *POPs* were investigated, and plastic ingestion and entanglement were documented. Chlorinated pesticides, *PCBs*, and *PBDEs* were found in the liver of a *R. lalandii* specimen caught during trawling operations off the coasts of Brazil (Cascaes et al. 2014). *PCBs* were present in greater amounts, followed by organochlorine pesticides and *PBDEs*. Miranda and de Carvalho-Souza (2016) documented microplastic pellet ingestion in two specimens upon analyzing stomach content of six individuals. Plastic debris was also found in three juvenile Brazilian sharpnose sharks caught in gillnets in southeast Brazil (Sazima et al. 2002). These sharks presented with plastic collars around their gill region; the tissues were severely damaged by these rings, which probably affected normal feeding and ventilation (Sazima et al. 2002). In the Pacific sharpnose shark, trace elements were principally investigated. The first study on this species was by Hurtado-Banda et al. (2012), who evaluated THg in the muscles and liver of 12 juveniles and 14 adults collected from artisanal fishery landing sites in Sonora (Mexico). Adults had higher THg values than juveniles, and in both age classes, muscle tissue was more contaminated. In the study by Frías-Espericueta et al. (2014), Cd, Cu, Pb, and Zn in the liver, muscle, and embryo-related tissues (placenta and umbilical cord) of 15 pregnant females and their embryos were investigated. Cu and Zn had higher values in the placenta and umbilical cord, whereas Pb and Cd were predominant in the maternal muscle and liver, respectively. Another 20 pregnant females and their embryos were sampled, and their blood, placenta, umbilical cord, and embryo livers were analyzed for THg (Frías-Espericueta et al. 2015). Maternal blood had higher values whereas embryonic liver had lower values. They found marked correlations between the THg content in the maternal blood, umbilical cord, and placenta, suggesting transplacental Hg transfer. Frías-Espericueta et al. (2019) also conducted a risk assessment for this species. They evaluated the THg in the edible muscles of 15 adult sharks caught by artisanal fisheries. The results showed that only 6.6% of the sharks sampled had mercury levels that exceeded the permissible limit; however, overall, the hazard quotient values for THg and the calculated methylmercury content indicated no risk upon consumption. These levels, however, might represent an additional stressor to the species, on top of bycatch and overfishing. All these studies, except the one by Moore et al. (2015), were published after the last assessment of the species, which indicates that an update is needed.

In addition, it can be seen from Table I that more than a third of the species are classified as DD, seven out of 17 species belong to threatened categories (VU, EN, and CR), and the remaining four species are not threatened. Only 10 out of 19 species are considered to be affected by pollution. The main source of contamination for these species is "9.1.3. Type unknown/unrecorded", which falls under the class "9.1. Domestic and Urban Wastewater". This class includes unidentified water-borne sewage and non-point runoff from housing and urban areas (nutrients, toxic chemicals, and/or sediments). The second most abundant class is the one that includes pollution from mining activities, a class assigned to four different species sharing the same area. This is followed by "9.2.1. Oil spills" and "9.3.2. Soil erosion and sedimentation" with three different species under each category. These categories include species who are affected, for example, from coastal sedimentation or from war-related oil releases, as some of these sharks inhabit the Arabian Gulf. As majority of these pollution classes are associated with the species due to their geographic range, it is not understandable why, for example, in the *Glyphis glyphis* assessment, there is no "Herbicides and pesticides" pollution threat. This species, which was assessed for the last time in 2005, inhabits an area where there is known contamination by several xenobiotics, including *DDT* (Von Westernhagen & Klumpp 1995; Haynes et al. 2000; Mortimer 2000).

As already mentioned before, some papers on the presence of pollutants in *Selachimorpha* do exist, although in a very limited number, and, to the best of our knowledge, only 11 of them demonstrate the effects of pollutants on these species. The studied species, their IUCN Red List Status, and the investigated biomarkers are listed in Table III.

Prionace glauca, Isurus oxyrinchus, Carcharodon carcharias, and the Mediterranean subpopulation of *Galeus melastomus* were assessed after the publication of their respective research papers; however, there is still no mention of pollution in the threat assessments of these species. The other species listed in the table were assessed before the publication of their respective papers; given the information that is now known, their conservation status should be updated.

Table II lists 32 *Batoidea* species, of which 34.2% occupy inland waters, 57.9% inhabit marine waters, and the remaining 7.9% are present in both ecosystems, allegedly living in estuarine areas. The predominant Red List category for these species was DD (12 species), followed by EN (seven species), VU (six species), LC (three species), CR, and NT (both two species). As for *Selachimorpha*, the pollution threat is recognized in species with very restricted ranges, some of which are very rare and are known only from a few specimens in museum collections (Compagno 2016a, 2016b). Although no *Selachimorpha* species is known to have a widespread distribution, in *Batoidea, Mobula birostris* represents the only species occurring in tropical, sub-tropical, and temperate waters of the Indian, Atlantic, and Pacific Oceans. Pollution threat is also recognized in other species with fairly wide distribution ranges, but they are limited in number (Carvalho et al. 2009; Rigby 2012; D'Anastasi et al. 2013; Kyne et al. 2013; Simpfendorfer 2013; Manjaji Matsumoto et al. 2016).

Pollution threats have mostly been assigned to species based on some potential and few documented risks (NOAA 2004a, 2004b; IGGC 2007; Mudd & Patterson 2010; Sheppard et al. 2010) associated with the areas they inhabit, as opposed to being based on ecotoxicological studies conducted directly on the specimens. Hence, as was mentioned for the *Selachimorpha*, because all these species inhabit coastal waters, estuarine environments, and freshwater ecosystems in states and regions that were or are known to use chemicals for agriculture (Forget 1991; Laabs et al. 2002; Hjorth et al. 2011; Rao et al. 2017; Mahzabin & Rahman 2017; Carvalho 2017; Rivai et al. 2019), they should all be classified under the "Herbicides and Pesticides" pollution class. We wanted to further verify whether there were scientific papers on contaminants in these species; upon investigating the available literature, it was found that none of the species listed in Table II had any studies conducted on them concerning pollutants. Nevertheless, ecotoxicological data is available for other species, both on pollutant concentrations and biomarker responses (Bezerra et al. 2019; Lyons & Wynne-Edwards 2019; Cagnazzi et al. 2019a, 2019b), and their assessments should be updated. Pollution categories assigned by IUCN to assessed *Batoidea* and *Selachimorpha* are summarized in Figure 1.

Selachimorpha and *Batoidea* have the same pollution threat classes, with the exception of "9.3.1. Nutrient loads" for *Batoidea* and "9.4. Garbage and Solid Waste" for *Selachimorpha*. In particular, these classes are assigned to three sawfish species, three freshwater and inshore ray species, and one coastal shark species. Regarding "Nutrient loads", no records of pollution stress were directly investigated on the animals, whereas the "Garbage and Solid Waste" threat was assigned to the Brazilian sharpnose shark because, as mentioned before, Sazima et al. (2002) observed three individuals with plastic pieces around the head and gill region.

The Mediterranean case

As already mentioned, pollution is an issue that concerns the majority of the aquatic ecosystems. Some regions are considered more polluted than others; an example is the Mediterranean Sea. It is a landlocked sea, has large urban and industrial concentrations along its shores, and supports heavy maritime traffic; therefore, these conditions make it particularly prone to considerable anthropogenic impact at every marine level (Naso et al. 2005; Fossi et al. 2006; Berrojalbiz et al. 2011; Bonanno & Raccuia 2018; Casini et al. 2018; Marsili et al. 2018). Despite its small size, the Mediterranean Sea is considered a biodiversity hotspot. Approximately 10% of the world's marine species are present in its waters and 20% to 30% of the Mediterranean Sea species are endemic (UNEP-MAP, 2010). The Mediterranean Sea is also characterized by a remarkable occurrence of Chondrichthyan species; most of them are considered "Endangered" or "Critically Endangered" as per the last IUCN regional

Table III. Bibliographic research on biomarkers tested in shark species. In brackets, the regional assessment (Mediterranean).

Species	Common name	IUCN Red List status	Investigated biomarkers	Reference
Schroederichthys chilensis	Redspotted catshark	DD	EROD, FAC	Fuentes-Rios et al. 2005
Scyliorhinus canicula *Galeus melastomus*	Lesser spotted dogfish Blackmouth catshark	LC, (LC) LC, (LC)	AChE, BChE, PrChE, LP	Solé et al. 2010a
Scyliorhinus canicula *Galeus melastomus*	Lesser spotted dogfish Blackmouth catshark	LC, (LC) LC, (LC)	CAT, GR, GST, EROD, CbE	Solé et al. 2010b
Prionace glauca	Blue shark	NT, (CR)	GR, GPx, GST, CAT, SOD, TBARS	Barrera-García et al. 2012
Prionace glauca	Blue shark	NT, (CR)	GR, GPx, GST, CAT, SOD, TBARS	Barrera-García et al. 2013
Isurus oxyrinchus	Mako shark	EN, (CR)	GR, GPx, GST, CAT, SOD, TBARS	Vélez-Alavez et al. 2013
Prionace glauca	Blue shark	NT, (CR)	GST, SOD, CAT, GR, GPx, TG, TBARS, AChE, IDH	Alves et al. 2016
Carcharodon carcharias	Great white shark	VU, (CR)	CYP1A, Vtg, Zrp	Marsili et al. 2016
Rhincodon typus	Whale shark	EN	CYP1A	Fossi et al. 2017
Carcharhinus leucas *Carcharhinus limbatus* *Sphyrna tiburo*	Bull shark Blacktip shark Bonnethead shark	NT NT, (DD) LC	EROD, GST	Cullen et al. 2019
Rhizoprionodon terraenovae	Atlantic sharpnose shark	LC	TG	Ehnert-Russo & Gelsleichter 2020

EROD = ethoxyresorufin-O-deethylase; FAC = fluorescent aromatic compounds; AChE = acetylcholinesterase BChE = butyrylcholinesterase; PrChE = propionylcholinesterase; LP = lipid peroxidation; TBARS = thiobarbituric acid reactive substances; CAT = catalase; GR = glutathione reductase; GST = glutathione-S-transferase; CbE = carboxylesterase; GPx = glutathione peroxidase; SOD = superoxide dismutase; TG = total glutathione; IDH = isocitrate dehydrogenase; CYP1A = cytochrome P450 1A; Vtg = vitellogenin; Zrp = zona radiata proteins

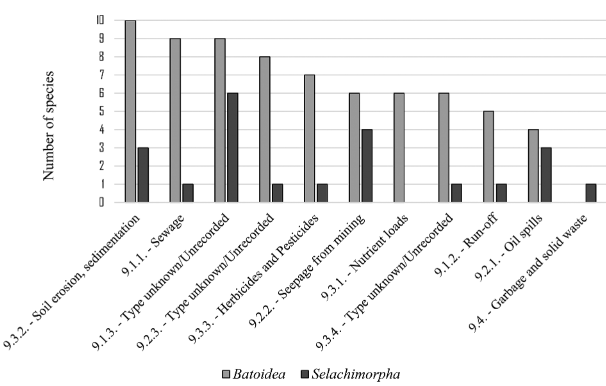

Figure 1. Assigned pollution categories to Batoidea and Selachimorpha assessed for pollution in the IUCN Red List. In particular, "9.1.3 - Type unknown/Unrecorded" falls into the "9.1. Domestic and Urban Wastewater" pollution class, "9.2.3 - Type unknown/Unrecorded" falls into the "9.2. Industrial and Military Effluents" pollution class, and "9.3.4 - Type unknown/ Unrecorded" falls into the "9.3. Agricultural and Forestry Effluents" pollution class.

assessment. In terms of the Mediterranean subpopulations, the IUCN Red List currently considers pollution as a threat for only two Chondrichthyan species: the bull ray (*Aetomylaeus bovinus*) and the undulate ray (*Raja undulata*). Previous studies on Mediterranean shark and ray species demonstrated the presence of *POPs* (Storelli & Marcotrigiano 2001; Storelli et al. 2004, 2005, 2011a, 2011b; Cresson et al. 2016) and trace elements (Kousteni et al. 2006; Storelli et al. 2002a, 2002b, 2011c), posing an additional stressor to their already threatened status. The importance of expanding the knowledge on pollution in these animals is fundamental. Indeed, as shown in Figure 2, there is a huge disparity between published papers on Chondrichthyes in general and published papers on pollution in these organisms.

The bibliographic research was conducted with two queries—*(Mediterranean sea OR Mediterranean) AND (elasmobranchs OR sharks OR batoids OR chondrichthyes)*—to search for papers on Mediterranean Chondrichthyes in general and *(Mediterranean sea OR Mediterranean) AND (elasmobranchs OR sharks OR batoids OR chondrichthyes) AND (contaminants OR organochlorines OR pollution OR DDT OR PCBs OR PBDEs OR PAHs OR mercury OR heavy metals OR plastic OR phthalates)* to search for papers on pollution in Mediterranean specimens. We refined

Figure 2. Published papers on Chondrichthyes in the Mediterranean Sea. In yellow, the percentage of papers on pollution in general (45 papers, 9%) and, in blue, the percentage of paper on other topics (445 papers, 91%).

the results, limiting the research to English articles/reviews in the final publication stage. Articles *in press* were not considered, nor were book chapters, theses, or conference papers/abstracts.

Conclusions

In conclusion, this review aimed to highlight the lack of information regarding pollution in cartilaginous fish. Herein, we demonstrated the need for an update in the conservation status of Chondrichthyes in the IUCN. Contamination is one of the primary stress factors in most marine organisms; it has already been demonstrated to be a substantial threat to cetaceans (Marsili et al. 2019), sea birds (Costantini et al. 2017; Dietz et al. 2019), and sea turtles (Casini et al. 2018). However, only a few papers exist on Chondrichthyes regarding the effect of pollution. Therefore, it is extremely important that contamination be considered as one of the priority stressors in the evaluation of their assessment. There are several environmental contaminants, most of which are still unknown and others are produced accidentally; many are highly persistent and bioaccumulative. Hence, Chondrichthyes, which are likely at the top of the food chain, are most at risk. In addition, the number of cartilaginous fish is declining worldwide (Sims 2015) as they are additionally threatened by factors such as overfishing, bycatch, target fisheries, and illegal trading. Moreover, given that some sharks and rays are also consumed by humans, it is risky to commercialize products that may be contaminated and lead to undesirable side effects (Mol et al. 2018; Kim et al. 2019; Lara et al. 2020). In addition, for this latter reason, it is fundamental to evaluate pollutant concentrations in edible tissues, both for Chondrichthyes conservation and maintenance of human health.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendix 1. Extract of the threats' classification scheme proposed by IUCN

Level of Classification (1 2 3)	Definition: Examples	Exposition
IUCN - CMP Unified Classification of Direct Threats		Direct threats are the proximate human activities or processes that have impacted, are impacting, or may impact the the status of the taxon being assessed (e.g., unsustainable fishing or logging). Direct threats are synonymous with sources of stress and proximate pressures. Threats can be past (historical, unlikely to return or historical, likely to return), ongoing, and/or likely to occur in the future.
9. Pollution	Threats from introduction of exotic and/or excess materials or energy from point and nonpoint sources	This class deals with exotic or excess materials introduced to the environment. There is obviously a fine distinction when the pollution comes from another threat - for example, should an oil spill from a pipeline be classified as **4.2 Utility & Service Lines or 9.2 Industrial & Military Effluents**? You will have to exercise some judgement here as to which represents the direct threat in your situation. In some cases, the source of the pollution may be either unknown or from a historical source (e.g., heavy metals buried in sediments). In these cases, you may have to make an educated guess as to which category to assign the pollutant.
9.1 Domestic & Urban Waste Water	Water-borne sewage and non-point runoff from housing and urban areas that include nutrients, toxic chemicals and/or sediments	This category does not include major industrial discharge, which falls under **9.2 Industrial & Military Effluents**. It does include chemicals and next generation pollutants (caffeine or pharmaceuticals) in household waste streams. Technically, sewage from a pipe is "point-source" whereas a leaking septic system is "nonpoint- source." This category does not include agricultural runoff, which falls under **9.3 Agricultural & Forestry Effluents.**
9.1.1 Sewage	List the source, and if possible, the specific pollutants of concern e.g., discharge from municipal waste treatment plants, leaking septic systems, untreated sewage, outhouses, etc.	
9.1.2 Run-off	List the source, and if possible, the specific pollutants of concern e.g., oil or sediment from roads, fertilizers and pesticides from lawns and golf-courses, road salt, etc.	
9.1.3 Type Unknown/Unrecorded		
9.2 Industrial & Military Effluents	Water-borne pollutants from industrial and military sources including mining, energy production, and other resource extraction industries that include nutrients, toxic chemicals and/or sediments	The source of the pollution is often far from the system – an extreme example are the heavy metals that migrating eels bring to the Sargasso Sea. Often, the pollutants only become a problem when they bioconcentrate through the food chain. Oil spills from pipelines should generally go here.
9.2.1 Oil Spills	List the source e.g., leakage from fuel tanks, oil spills from pipelines, PCBs in river sediments, etc.	
9.2.2 Seepage from Mining	List the specific pollutants if possible e.g., mine tailings, arsenic from gold mining, etc.	

(*Continued*)

(*Continued*).

9.2.3 Type Unknown/Unrecorded		There are other known examples of industrial pollution, which are not specifically captured under the classification scheme. These should be coded here for now, and the type/cause of the pollution noted in the text box. Examples include: toxic chemicals from factories, illegal dumping of chemicals, other industrial effluent, ship waste discharge, etc.
9.3 Agricultural & Forestry Effluents	Water-borne pollutants from agricultural, silivicultural, and aquaculture systems that include nutrients, toxic chemicals and/or sediments including the effects of these pollutants on the site where they are applied	Wind erosion of agricultural sediments or smoke from forest fires goes in **9.5 Air- Borne Pollutants**.
9.3.1 Nutrient Loads	List the source and specific pollutant of concern: e.g., nutrient loading from fertilizer run-off, manure from feedlots, nutrients from aquaculture, etc.	
9.3.2 Soil Erosion, Sedimentation	List the source and specific pollutant of concern: e.g., soil erosion from overgrazing, increased run-off and hence sedimentation due to conversion of forests to agricultural lands, etc.	
9.3.3 Herbicides and Pesticides	List the source and specific pollutant of concern: e.g., herbicide run-off from orchards, etc.	
9.3.4 Type Unknown/Unrecorded		
9.4 Garbage & Solid Waste	Rubbish and other solid materials including those that entangle wildlife	This category generally is for solid waste outside of designated landfills - landfills themselves should go in 1.2 Commercial & Industrial Areas. Likewise, toxins leaching from solid waste - for example, mercury leaking out of a landfill into groundwater - should go in 9.2 Industrial & Military Effluents.
List the type, source, and if possible, the specific pollutants of concern	municipal waste, litter from cars, flotsam & jetsam from recreational boats, waste that entangles wildlife, construction debris, etc.	
9.5 Air-Borne Pollutants	Atmospheric pollutants from point and nonpoint sources	It may be difficult to determine the sources of many atmospheric pollutants – and thus hard to take action to counter them.
9.5.1 Acid rain	List the source, and if possible, the specific pollutants of concern e.g., acid rain, excess nitrogen deposition, radioactive fallout, wind dispersion of pollutants or sediments, smoke from forest fires or wood stoves, etc.	
9.5.2 Smog	List the source, and if possible, the specific pollutants of concern e.g., smog from vehicle emissions, coal burning, wind dispersion of pollutants or sediments, smoke from forest fires or wood stoves, etc.	Smog is a type of air pollution derived from vehicular emission from internal combustion engines and industrial fumes that react in the atmosphere with sunlight to form secondary pollutants that also combine with the primary emissions to form photochemical smog. Smog is also caused by large amounts of coal burning in an area caused by a mixture of smoke, sulphur dioxide and other components.
9.5.3 Ozone	List the source, and if possible, the specific pollutants of concern e.g., vehicle emissions, factory smoke emissions, smoke from forest fires or wood stoves, wind dispersion of pollutants or sediments, etc.	Ozone is not emitted directly by car engines or by industrial operations, but formed by the reaction of sunlight on air containing hydrocarbons and nitrogen oxides that react to form ozone directly at the source of the pollution or many kilometres down wind.

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(*Continued*).

9.5.4 Type Unknown/Unrecorded		
9.6 Excess Energy	Inputs of heat, sound, or light that disturb wildlife or ecosystems	These inputs of energy can have strong effects on some species or ecosystems.
9.6.1 Light Pollution	List the source, and if possible, the specific pollutants of concern e.g., lamps attracting insects, beach lights disorienting turtles, etc.	
9.6.2 Thermal Pollution	List the source, and if possible, the specific pollutants of concern e.g., heated water from power plants, damaging atmospheric radiation resulting from ozone holes, etc.	
9.6.3 Noise Pollution	List the source, and if possible, the specific pollutants of concern e.g., noise from highways or airplanes, sonar from submarines that disturbs whales, etc.	
9.6.4 Type Unknown/Unrecorded		