SCIENTIFIC COMMITTEE
NINETHEEENTH REGULAR SESSION

Koror, Palau
16 – 24 August 2023

Evaluating publicly available reported shark and ray catch data in industrial fisheries: A global review to inform assessment and conservation

---

WCPFC-SC19-2023/EB-WP-09

Melissa R. Cronin[1,2,3], Jordan T. Watson[4], Nerea Lezama-Ochoa[2,5], Gala Moreno[6], Hilario Murua[6], Anna C. Nisi[7], Connor Price[1], Nathan G. Taylor[8], Donald A. Croll[1]

[1] Ecology & Evolutionary Biology Department, University of California, Santa Cruz, CA, USA
[2] Mobula Conservation, La Paz, Mexico
[3] Nicholas School of the Environment, Duke University, Durham, NC, USA
[4] Pacific Islands Ocean Observing System, Honolulu, HI, USA
[5] Institute of Marine Sciences, University of California, Santa Cruz, CA, USA
[6] International Seafood Sustainability Foundation, Pittsburgh, USA
[7] Biology Department, University of Washington, Seattle, WA, USA
[8] The International Commission for The Conservation Of Atlantic Tunas, Madrid, Spain

Corresponding author:
Melissa R. Cronin
melissa.cronin@duke.edu

Executive Summary

Several species of sharks and rays are experiencing severe population declines, yet clarity about where to focus management and conservation actions is lacking. Industrial tuna fisheries target or incidentally catch (i.e., "bycatch") vulnerable shark and ray (i.e., elasmobranch) species in significant numbers, with potentially long-lasting impacts. However, due to often limited research-grade data collection and access, the contribution of these fisheries to elasmobranch mortality is often incomplete, regionally focused, and poorly understood. Here, we used quantitative and qualitative approaches to quantify publicly accessible pelagic elasmobranch catch data in four tuna Regional Fisheries Management Organizations (tRFMOs) and describe the scale and potential impact of industrial tuna fisheries on 13 threatened oceanic shark species and 9 mobulid ray species. We compiled publicly reported catch data and estimated that tRFMO-managed purse seine and longline fisheries reported an annual mean of 2.4 million individual pelagic elasmobranchs (91,954 tonnes) over the last years with available data (2013–2019), corresponding to roughly one elasmobranch reported for every two tonnes of tuna caught. Longline fishing is responsible for >90% of this reported catch, due primarily to the commercial status of some elasmobranchs. Based on existing stock assessments, only 20% of the examined populations have been formally assessed, and assessments are uncommon for species that are not commercially targeted. These results present a broad characterization of publicly available global and regional reported elasmobranch catch data, and can guide improved data collection and access, research, and conservation efforts for increasingly vulnerable oceanic elasmobranchs.

1. Introduction

One third of shark, ray, and closely related species (i.e., elasmobranchs) are threatened with extinction, and the global abundance of pelagic sharks and rays is estimated to have declined by 71% since 1970 (Dulvy et al. 2021; Pacoureau et al. 2021). In some cases, this decline can perturb pelagic ecosystems over large spatial and temporal scales (Stevens 2000; Ferretti et al. 2010; Heupel et al. 2014). Economically, this decline may contribute to loss to some coastal communities where elasmobranch fisheries support food security and livelihoods (Simpfendorfer & Dulvy 2017) as well as loss of elasmobranch-related ecotourism (Dent & Clarke 2015; Healy et al. 2020). Beyond their economic value, elasmobranchs are important to many Indigenous cultures around the world, and their loss may compromise the prominence of socially important resources and symbols (Leeney & Poncelet 2015).

Multiple anthropogenic stressors have led to population declines of pelagic elasmobranchs, including targeted harvest for meat, fins, gills, and other body parts; bycatch (here defined as the portion of the catch that is unintentionally captured and discarded alive or dead (Hall 1996; Davies et al. 2009)); climate change (Osgood et al., 2021); habitat loss; and possibly pollution (Germanov et al. 2018). However, fishing impacts—both targeted and bycatch—are the primary drivers of pelagic elasmobranch declines (Dulvy et al. 2021; Juan-Jordá et al. 2022). Because of their vulnerability, which is exacerbated by their general life history traits including low fecundity, delayed maturation, slow growth rates, and long life spans, shark and rays are less resilient to exploitation than other fishes (Stevens 2000; Dulvy et al. 2008).

Among pelagic elasmobranchs, there has been particular concern for a subset of 13 pelagic shark and nine mobulid ray species (Table 1). These species were recently listed (except blue shark - *Prionace glauca*) under Appendix II of the Convention on International Trade in Endangered Species (CITES), which restricts international trade (Lawson et al. 2017). Additionally, all species except blue shark were listed on the Convention for Migratory Species (CMS), which helps set conservation priorities and policy guidance for species whose ranges straddle international boundaries. These listings have brought more international attention to understanding the primary threats to pelagic elasmobranchs (Vincent et al. 2014; Cardeñosa et al. 2018). As a result, recent conservation efforts from non-governmental organizations have focused on marketing campaigns to reduce consumer demand for shark meat and fins or banning their trade in some regions, although these appear to have had limited success (Clarke et al. 2007; Ferretti et al. 2020). Nonetheless, while listings on biodiversity treaties like CITES and CMS can be useful to attract conservation attention and regulate international trade of these species, many species listed on both agreements continue to face immediate threats (Fowler et al. 2021) (Lawson & Fordham, 2018; Fowler et al. 2021).

Globally, the capture of pelagic elasmobranchs is greatest for longline, gillnet, and purse seine gears, which are the main methods used to target tuna and other high-value tuna-like species by industrial fisheries (Oliver et al. 2015; Croll et al. 2016). Elasmobranchs are considered bycatch in many of these fisheries, though some fisheries using longlines target (e.g., blue shark, *Prionace glauca*) or opportunistically retain some elasmobranch species (e.g., shortfin mako, *Isurus oxyrinchus)* (Clarke et al. 2014; Booth et al. 2020). Because tuna vessels using these gears, particularly longline, overlap in space, time, and depth with pelagic elasmobranch habitat (Queiroz et al. 2019; Murua et al. 2021), these elasmobranch species can comprise as much as 12% to 25% of the total catch in some tuna longline fisheries, even when they are not targeted (Gilman et al. 2008; Gilman 2011; Coulter et al. 2020). However, low observer coverage, poor catch reporting practices, and retention bans for some species—coupled with lack of incentives to carefully manage non-target species in many fisheries—has made it difficult to assess the scale and impact of tuna fishery interactions with elasmobranchs, though it is considered an important threat (Barker & Schluessel 2005; Molina & Cooke 2012; Oliver et al. 2015; Jorgensen et al. 2022; Mucientes et al. 2022). Moreover, although some fisheries release incidentally caught elasmobranchs alive, post-release mortality studies in tuna longline and purse seine fisheries have shown that survival varies widely between species, gears, and handling and release methods (Gilman et al. 2008; Hall & Roman 2013; Hutchinson et al. 2015; Musyl & Gilman 2019; Hutchinson 2021).

Pelagic fisheries that target tuna and tuna-like species fall broadly under the management of five oceanic tuna Regional Fishery Management Organizations (tRFMOs), each of which facilitates data collection, research, conservation, and fishery management in its respective Convention Area. In recent years, there has been increasing recognition (including within their own convention texts, e.g. the Antigua Convention in the Eastern Pacific Ocean) that tRFMOs should maintain or restore populations of non-target species at biologically sustainable levels (Clarke et al. 2012; de Bruyn et al. 2013). In response, all tRFMOs have adopted management measures for pelagic elasmobranchs (Cullis-Suzuki & Pauly 2010; Tolotti et al. 2015; Juan-Jordá et al. 2018; Heidrich et al. 2022). However, with the exceptions of blue shark and shortfin mako in the Atlantic Ocean, there are no limits imposed on their catch (though landing and retention bans exist for several species) (Sims & Queiroz 2016, ICCAT 2019). While there is growing concern about the impact of coastal artisanal fisheries that are largely unregulated and extremely data-poor (Martinez et al., 2015, IATTC 2020; Oliveros-Ramos et al. 2020; Lennert-Cody et al. 2022), there are relatively better elasmobranch data for industrial tuna fisheries to develop effective management measures for industrial tuna fisheries. As a result, there is both a critical need for improved management and conservation of pelagic elasmobranchs within industrial tuna fisheries (Jorgensen et al. 2022).

While the unsustainable impacts of tuna fisheries on pelagic elasmobranchs was identified as a management issue more than a decade ago (Clarke et al. 2006; Gilman et al. 2008), recently observed shark population declines warrant finer-scale investigation to determine which fisheries may be contributing to these trends (Dulvy et al. 2021; Pacoureau et al. 2021). A lack of reliable fine-scale data has stymied global analyses of the scale of elasmobranch catch in fisheries in general, and tuna fisheries in particular (Heidrich et al. 2022). However, recent developments in data accessibility, including the publication of public domain datasets of comparable reported species catches, offer an opportunity to describe and assess pelagic elasmobranch catch in multiple oceans in a standardized way (Le Manach et al 2016; Williams et al. 2016; Taconet et al. 2017; Coulter et al. 2020). Further, all five tRFMOs have recently undertaken efforts to assess the impact of tuna fishing on the population status of sharks and rays (Clarke et al. 2013; Dent & Clarke 2015; Griffiths et al. 2019), including stock assessments (e.g., Kleiber et al. 2009; Rice 2013, 2017; Heidrich et al. 2022) and ecological risk assessments (e.g., Arrizabalaga et al. 2011; Hobday et al. 2011; Murua et al. 2012, 2018; Griffiths et al. 2019, 2022; IATTC 2022). Finally, though recent studies have sought to evaluate the impact of fishing on pelagic fishes (Heidrich et al. 2022; Juan-Jordá et al. 2022), no study has sought to broadly evaluate global elasmobranch catch in tuna fisheries at species-level resolution, which is the level necessary for informed conservation and management.

In this study, we aggregate and synthesize knowledge on the reported catch to tRFMOs and estimate potential capture of 13 shark species and 9 ray species. Specifically, we aimed to examine: 1) the quantity and composition of reported elasmobranch catch in tRFMOs and 2) the proportion of reported pelagic elasmobranch catch that is i) formally assessed and considered overexploited by a stock assessment, and ii) considered threatened according to the IUCN Red List. This synthesis uses several data sources to understand the potential impacts of tuna fisheries on elasmobranchs as well as providing guidance for future elasmobranch research, conservation, and management more broadly.

2. Materials and Methods

Publicly available elasmobranch catch data that is reported to tRFMOs by its Members and Cooperating non-members (data summarized from vessel logbooks and/or observer programs) was downloaded from tRFMO websites (Table S1). These data were used to describe patterns in reported catches by species, gear type, and ocean, and to describe the proportion of the catch that is publicly reported to compare to overall tuna catch in each region. To evaluate the potential sustainability of these catches, published stock assessments and IUCN Red List designations were used for each stock and species, respectively.

These reported data are referred to as “catch”, but it is important to note that this catch consists of incidental catch (i.e., bycatch) as well as, in certain occasions, targeted catch. We examined all reported catch over the last half century, from 1970 (when the first substantial elasmobranch catch reports occurred) to 2020. However, because differences in observer coverage and data reporting between gears and oceans likely present biases in the quality of the data over time, we constrained some analyses to the period from 2013 to 2019, the years in which data was available from all tRFMOs. We focused our analysis on four major tRFMOs (Inter-American Tropical Tuna Commission (IATTC), International Commission for the Conservation of Atlantic Tunas (ICCAT), Indian Ocean Tuna Commission (IOTC), and Western and Central Pacific Fisheries Commission (WCPFC)) that manage tropical tuna fisheries (Table S1). The Commission for the Conservation of Southern Bluefin Tuna was excluded from this analysis, as it is a unique special commission for fisheries targeting only one temperate tuna species, which overlaps with the convention areas of the other tRFMOs.

2.1 Characterizing reported catch

Three main sources of publicly available data from tRFMO websites were used: 1) elasmobranch catch, 2) tuna catch, and 3) stock assessments. Data sources for each tRFMO are described in Table S1. For the elasmobranch catch data (1), available public datasets, which were sourced opportunistically from observer data (IATTC, WCPFC) and logbook data (IOTC, ICCAT) were downloaded from each tRFMO website. Because data from artisanal fisheries are either scant, unreliable, or not representative of entire fleets, data were constrained to include catches from industrial purse seine and longline vessels only. However, we acknowledge that pelagic elasmobranch catch from smaller vessels being a likely source of substantial mortality, particularly in the Indian Ocean (Murua et al. 2018), eastern Pacific Ocean (Martinez-Ortiz et al. 2015), and elsewhere.

Where available, information on gear type was included. Data for species representing the genera *Alopias, Isurus, Mobula,* and the family *Sphyrnidae* were generally available only as species aggregations at the genus or family level in most data sources, likely because of difficulty in accurately identifying individual species. Therefore, species within each taxonomic aggregation were analyzed together (Table 1).

Because two tRFMOs (IOTC and ICCAT) report elasmobranch catch data in tonnes and two (IATTC and WCPFC) report in individuals, data was harmonized using a hierarchical process. First, where available, average sizes were computed from observer-collected length data for each species and gear (using only data for 2013–2019) (e.g., mean length for silky sharks caught in purse seine gear in the Atlantic Ocean). This data was available upon request from IATTC and was publicly available from IOTC and ICCAT for most species and gears. Second, where these data were not available within these three tRFMOs, mean length was computed from available length estimates for that species and gear in other tRFMOs. Third, if no region- and gear-specific data were available from any tRFMO data or documents, we reviewed the scientific literature for length measurements and conversion parameters that can be used for each species and gear as a next best estimate. For example, for WCPFC, length data was not available; thus, mean lengths were calculated by averaging data available for species caught in the same gear type from other oceans. Because sex distribution of the catch was generally not available, we did not differentiate by sex (Curran & Bigelow 2016).

These data were used to calculate weight using the equation $W = a * L^b$, where L is length, parameter a is the intercept of the line and parameter b is the slope of the line (Table S2). For data that were grouped by genus or family (e.g., *Alopias, Sphyrnidae, Isurus,* and *Mobula*), gear-specific species weights were first calculated, then averaged to produce a mean genus or family weight.

2.2 Evaluating sustainability of catches

We sought to match the populations (referred to as "stocks") included in this study with existing fishery stock assessments, which can determine stock status, including whether it is either overfished (the biomass is below a reference biomass value), subject to overfishing (the fishing mortality is above a reference fishing mortality), both, or experience neither (not overfished or no overfishing, respectively) (Begg et al. 1999). Stock assessment documents published on tRFMO websites and in the scientific literature were collected and matched to reported catch data for each species and ocean. Except for some mobulid rays and the pelagic thresher, all species in this study are globally distributed (Table 1); thus, for each tRFMO, we considered only species that is within the tRFMO's remit as eligible for stock assessment for each tRFMO (Table S3). In cases where a population had more than one assessment, the most recent assessment was selected. In a case where a population was split into two or more stocks in one ocean based on genetic structure, we included both designations but, for simplicity, considered them a dual designation for that population in that ocean. If the assessment did not result in a conclusive status determination, it was characterized the result as "unknown." If an assessment was conducted for a migratory species in more than one tRFMO (e.g., if an assessment was intended to assess trends in more than one convention area across the population's range—for example, a Pacific-wide assessment for silky shark), this assessment was considered applicable to that species in all tRFMOs within the geographic scope of the study.

In addition to stock assessments, IUCN Red List risk assessment designations were included as a contextual indicator of conservation status, as is common for pelagic elasmobranchs (Dulvy et al. 2021; Pacoureau et al. 2021; IUCN 2022). Where two species within a genus that are reported together in the catch data had different IUCN designations (e.g. mobulids, two of which are considered Vulnerable, and seven of which are considered Endangered), the more conservative listing for that genus was used, following the precautionary approach (e.g., Endangered for mobulids).

3. Results

3.1 Characterizing reported catch (1970 – 2019)

Reported catch of pelagic elasmobranchs totaled roughly 52 million individuals over the study period and has increased for both longline and purse seine gears over the last half-century. Catches were dominated by longline gear, representing 97.9% of total catch from 1970 to 2019 (n= 51,057,515 individuals or 1,972,110 tonnes), while purse seine gear represented 2.3% (n= 1,211,865 individuals or 31,460 tonnes) (Fig 1A). Reported catch over this period peaked in 2016 with 2.6 million individuals (99,828.7 tonnes). The longline and purse seine catches were each dominated by blue shark (80.9%) and silky shark (77.5%), respectively, and the quantity of reported catch varied widely by species (Fig1B).

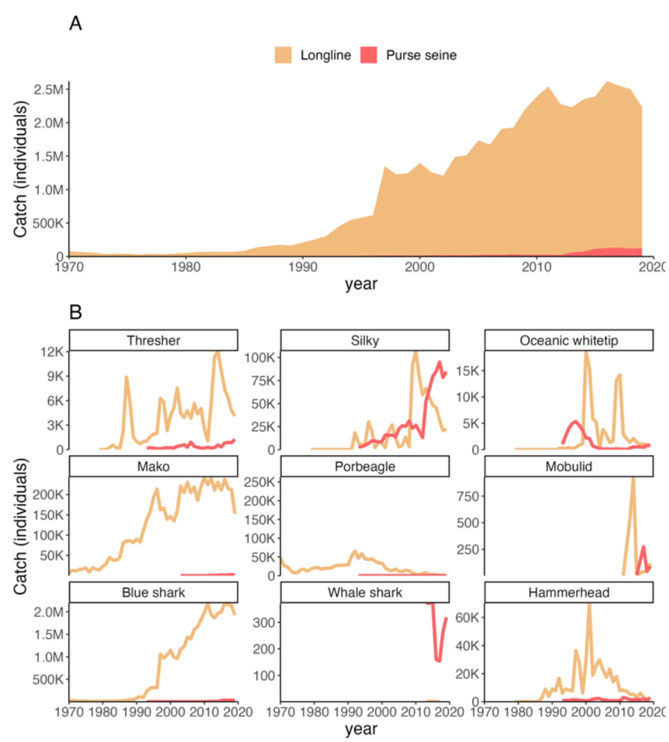

Fig 1. Publicly reported catch data indicates that A) reported elasmobranch catch in longline and purse seine tuna fisheries has increased in the last ~50 years, mainly attributed to longline fisheries, and B) the quantity of reported catch varies widely by species and/or genus (note panels have different y-axes).

Across all gear types and species, ICCAT reported the largest proportion of the combined total catch of elasmobranchs (83%), followed by IOTC (13%), IATTC (2%), and WCPFC (1%) (Fig. 2A). Some species included in this study were missing from publicly reported data, including: Mobulids in WCPFC and IATTC, porbeagle in ICCAT, and whale sharks in IATTC and IOTC (Fig 2B).

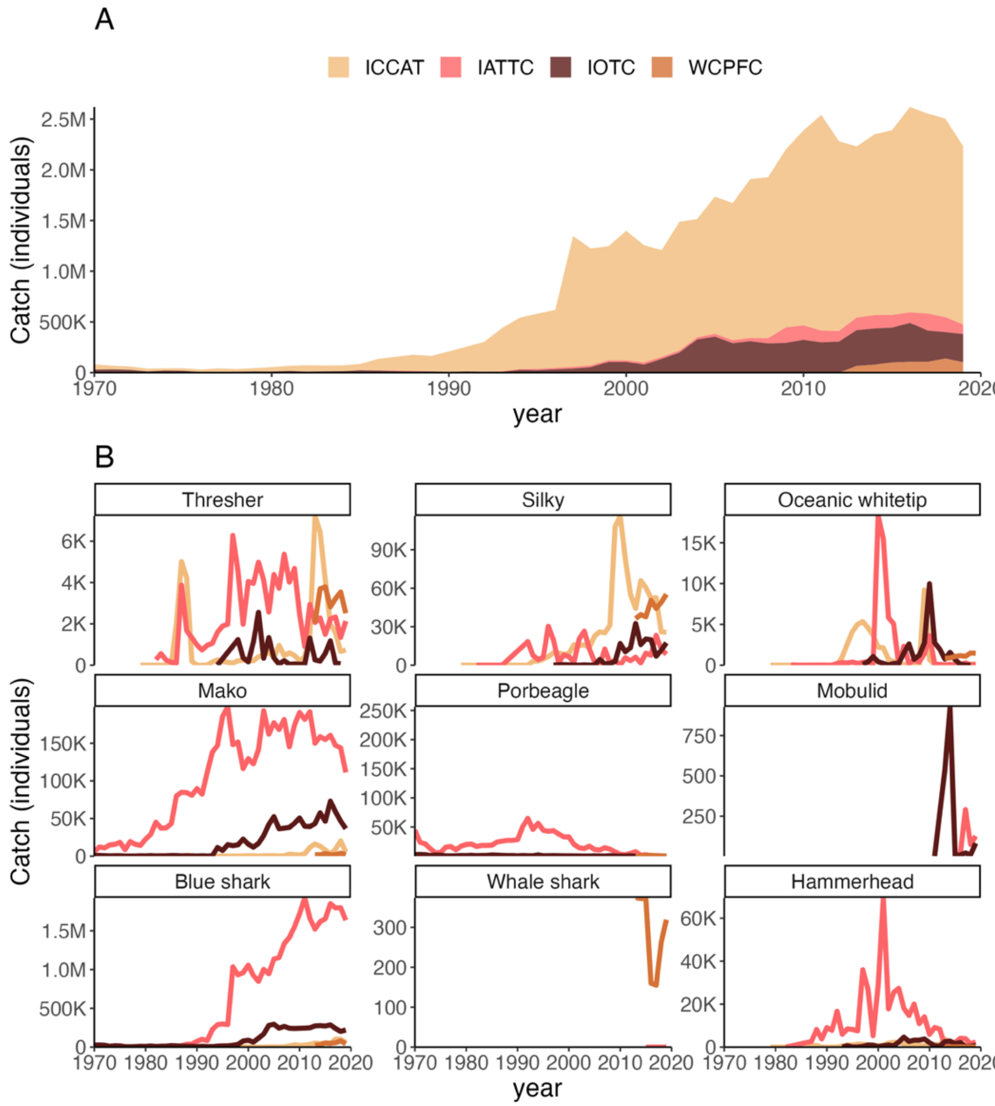

Fig. 2. Publicly reported catch data from tRFMOs over the past half century indicates a recent peak of roughly 2.6 million individuals reported in 2016, mainly reported by ICCAT. Note panels have different y-axes.

3.2 Characterizing recent annual catch (2013 – 2019)

For the recent analysis period of 2013–2019, during which all tRFMOs reported elasmobranch data, the annual average reported elasmobranch catch was 2,411,939 (sd = 153,092) individuals (91,954 tonnes; sd = 5,615). Similar to results from the longer analysis period, 95% of this catch was attributed to longline gear (Fig 3A), and most (83%) of the catch in longline gear was attributed to blue shark (Fig 3C).

Most (77%) of the recent overall reported catch was reported by ICCAT. However, within purse seine gear alone, reported catch was mainly from WCPFC (45%), IATTC (30%), and ICCAT (25%), while IOTC reported near-zero purse seine elasmobranch catch (Fig 3B).

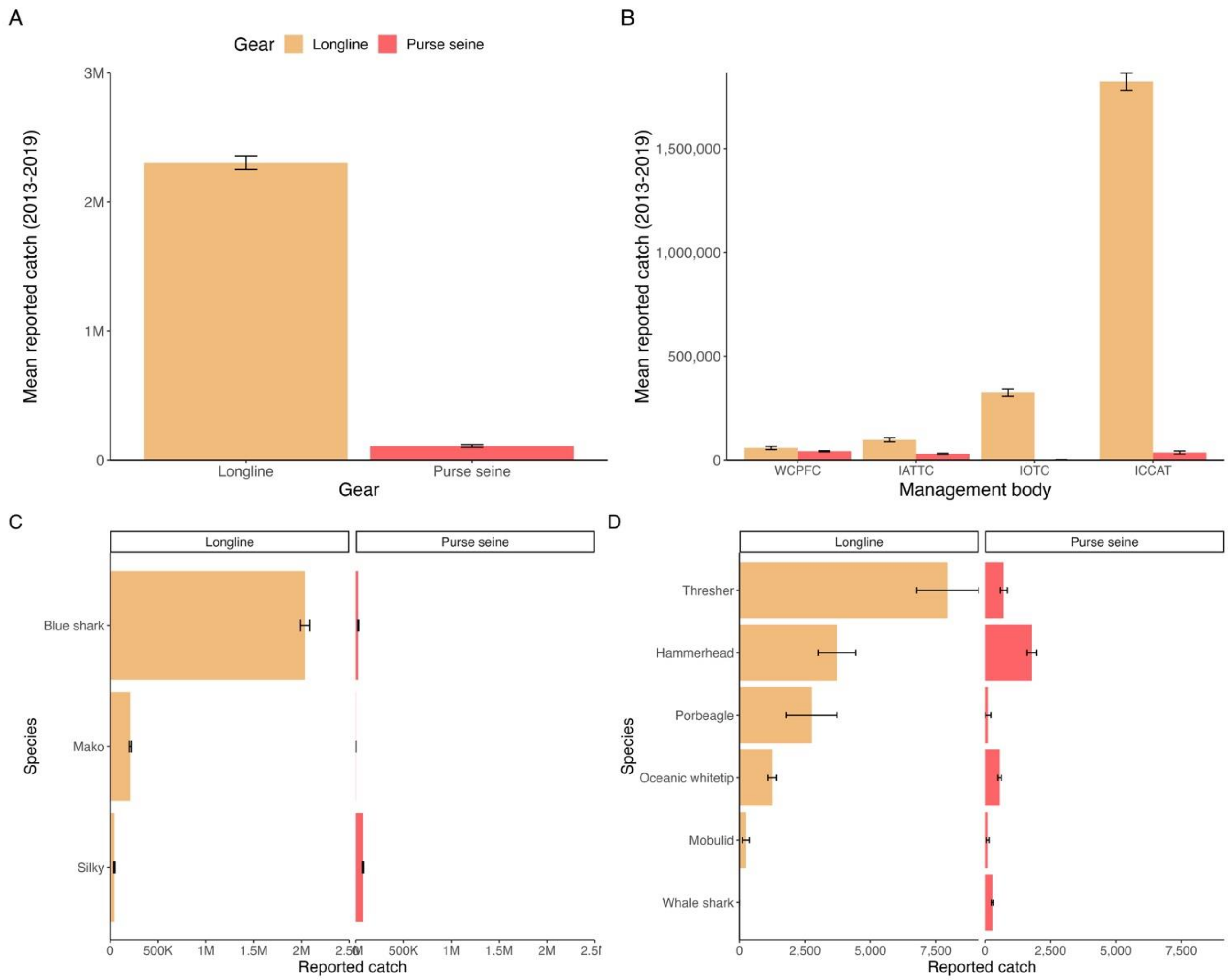

Fig 3. Annual average catch data in tuna fisheries from reporting data indicates for recent years (2013 – 2019) shows that A) reported catch totals roughly 2.4 million individuals on average for this period, mainly attributed to longline gear, and B) some tRFMOs, namely ICCAT and to a lesser extent IOTC, comprise the majority of recently reported catch data. Reported data for elasmobranchs were grouped into C) more abundant species and D) less abundant species (note different panel x-axes).

3.4 tRFMO species data gaps

IATTC releases public domain data in individuals for longline vessels as target catch and for purse seine fisheries as bycatch. IATTC does not report data for mobulids or whale sharks (Fig 5).

ICCAT releases public domain data in tonnes for longline vessels as target catch and for purse seine fisheries as bycatch. ICCAT does not report data for mobulids or whale sharks (Fig 5).

IOTC releases public domain data in tonnes for longline gear and purse seine gear. Purse seine data for elasmobranchs was sparse for IOTC; and was entirely missing for the years 2014-2016; thus reported catch could not be calculated for those years. IOTC does not report data for whale sharks (Fig 5).

WCPFC reported elasmobranchs in individuals as part of public domain bycatch datasets for purse seine and longline gears. Though WCPFC reports the highest volume of target tuna (Fig S1), overall reported elasmobranch was lowest among the tRFMOs (Fig 4B). WCPFC does not report data for mobulids (Fig 5G).

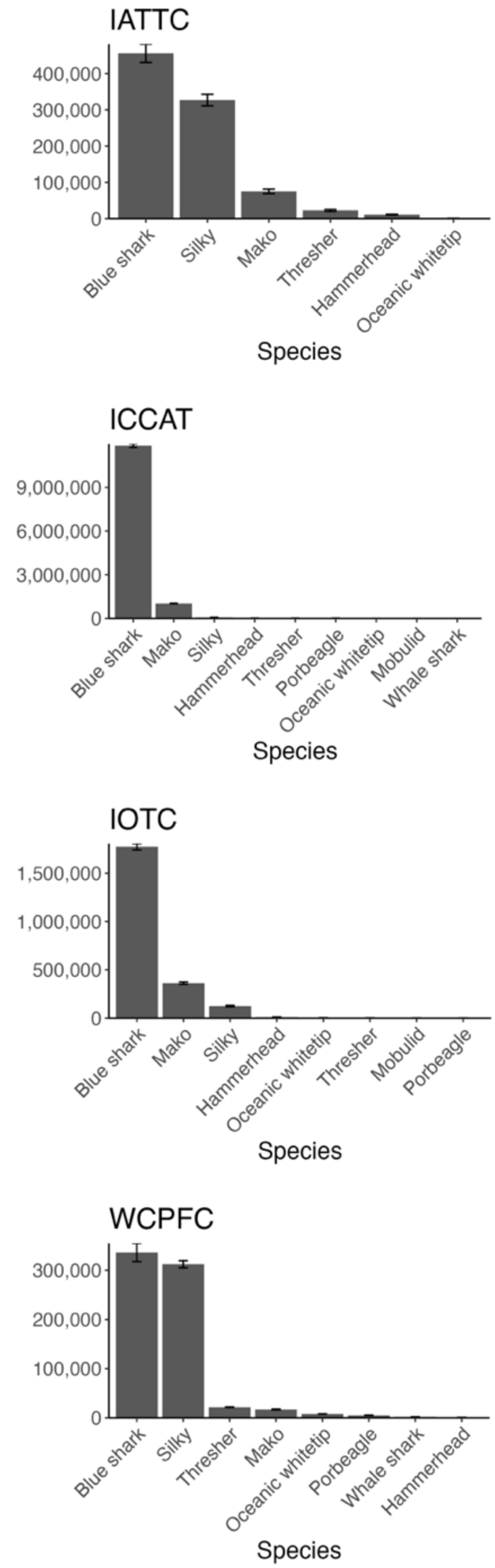

Fig 5. Species/genus as proportion of total annual mean catch reported to each tRFMO.

1.1Matching stock assessments to reported catch

A total of 19 conclusive stock assessments that determine stock status were identified, which represented ~20% (n=15) of the 76 eligible elasmobranch populations across all four tRFMOs (Fig 6A); though these Of the 19 stock assessments examined, nine assessments indicated that a stock was considered "overexploited" (*overfished* and/or *overfishing occurring* for at least one population within the stock) (Table 3).

When examining stock status as a proportion of overall reported catch, assessed stocks pertain to 96.5% of the annual reported catch (Table 3, Fig 6B). Assessed stocks considered overexploited represent ~11% (n=261,964) of the reported annual elasmobranch catch by weight (6.1% *overfished* and *overfishing occurring;* 4.7% *overfishing occurring;* Figure 6B). Stocks considered not overexploited (*not overfished* and *no overfishing occurring*) represented 85.6% n=2,065,548) of the annual reported catch by weight. Reported catch from stocks whose status is unknown (including those species assessed without a conclusive designation and those not yet assessed) represented 3.5% of the reported catch (n=84,586). Blue shark caught in longlines in the Atlantic comprised most of the catch designated *not overfished* and *no overfishing.* (Fig 6A, 6B). When examining tRFMOs individually, IATTC had the greatest proportion of stocks with unknown status (49%), while WCPFC had the highest proportion of overexploited stocks (45%).

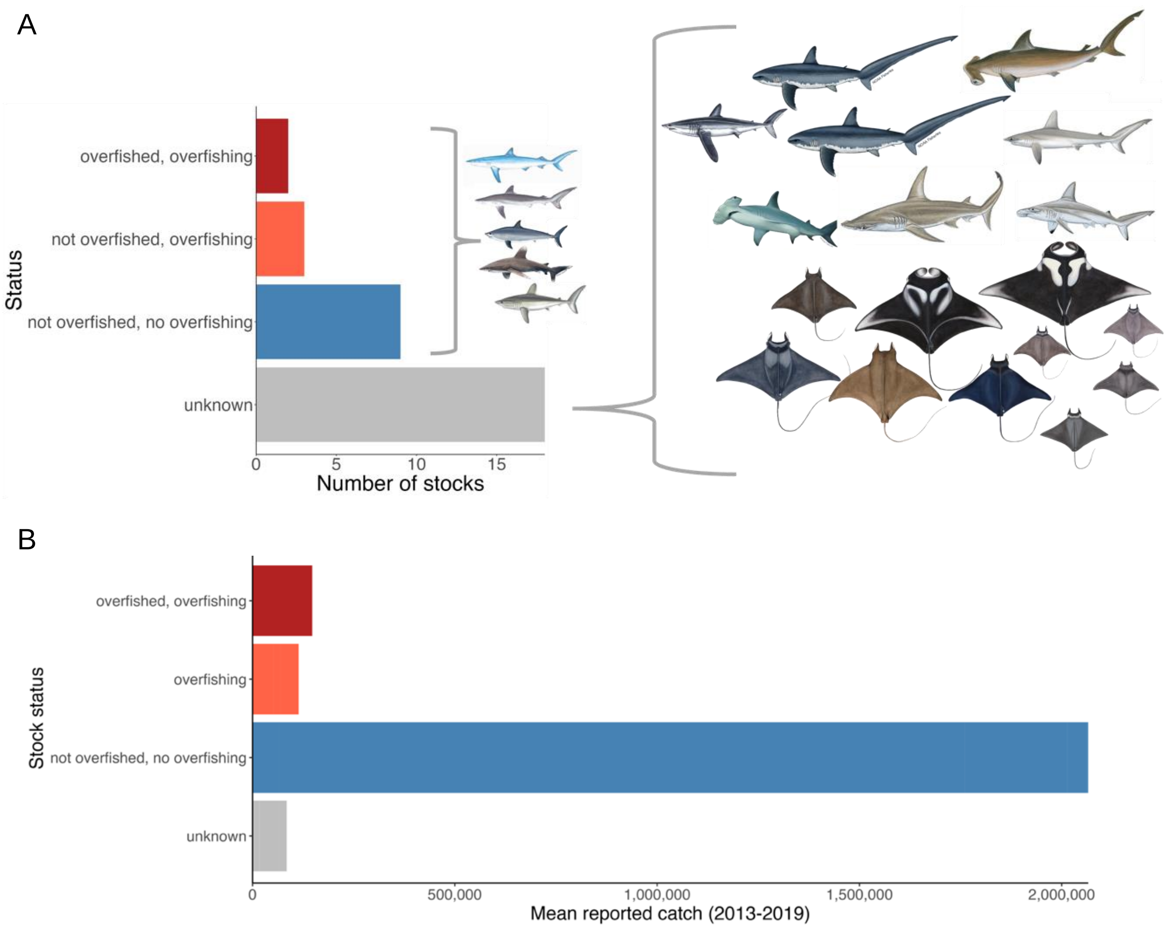

Fig 6 Stock assessment status of reported annual elasmobranch species in tRFMOs (2013–2019) for A) number of stocks of eligible elasmobranchs and B) as a proportion of total reported elasmobranch catch. Shark images credited to NOAA Fisheries; mobulid images credited to Life Sciences Studios.

Annual reported catches of individuals were matched with global IUCN Red List designations. We found that 21.4% (n= 561,662) of the reported catch was designated "threatened", including 0.3% considered Critically Endangered (n=7,379), 8.4% considered Endangered (n=220,870), and 12.7% considered Vulnerable (n=333,412) (Fig 7). The remaining 79% of pelagic elasmobranch catch is considered 'Near Threatened' by the IUCN Red List (n = 2,061,969), consisting entirely of blue shark.

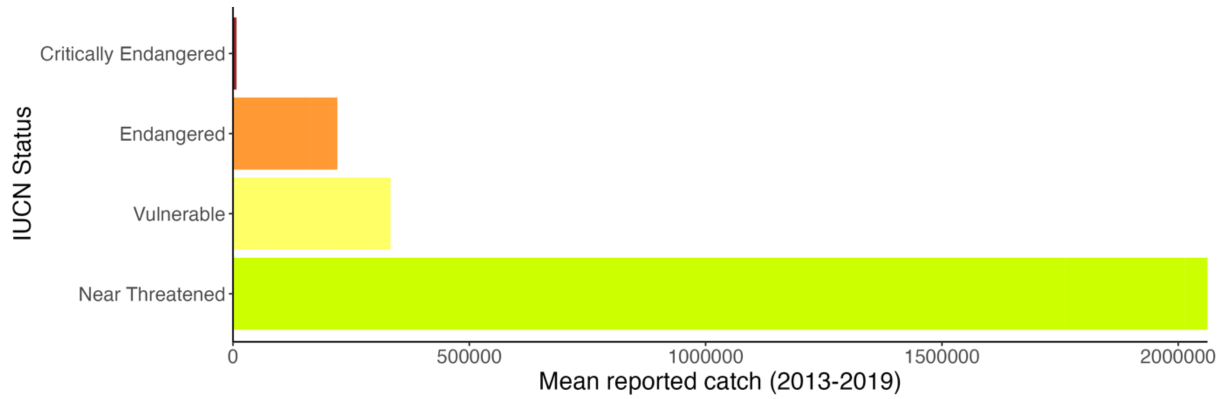

Fig 7 IUCN Red List designation as a proportion of reported annual elasmobranch catch in tRFMOs (2013–2019) for all tRFMOs together.

2. Discussion

We present a global characterization of publicly available reported catch data for pelagic shark and ray catch in both industrial purse seine and longline tuna fisheries, which together represent 78% of commercial tuna captured globally (FAO 2020). We paired our analysis of reported catch data with target catch data and published stock assessment data to contextualize this catch within broader tuna fishery management settings.

2.1 Patterns in elasmobranch catch

We found that tuna fisheries report roughly 2.4 million pelagic elasmobranchs captured annually in recent years, with the majority (95%) of this reported catch occurring in longline fisheries. This is surprising, as longline tuna fisheries generally have far lower required observer coverage than purse seine fisheries (Table S1)—in fact, many longline fisheries have less than 5% observer coverage required, while all tRFMOs but IOTC require 100% observer coverage for industrial purse seine vessels. Thus, the higher magnitude of reported catch in longline fisheries compared to purse seine is even more striking, given likely underreporting in longline fisheries.

Indeed, longline gear is responsible for 95% of total reported elasmobranch catch, but yields <23% of tuna production in any ocean (Clarke et al, 2014). This suggests that purse seine fishing may be a relatively less impactful fishing mode for pelagic elasmobranchs. Although, it is important to note that this analysis does not account for the impact of potential passive fishing (also called "ghost fishing"); for example from the use FADs in purse seine fishing, which can entangle and kill elasmobranchs (Filmalter et al. 2013). However since 2013, tRFMOs have adopted lower risk entanglement FAD designs in recent years to minimize ghost fishing mortality (Moreno et al. 2018; Murua et al. 2023).

Further, low observer coverage in the Indian and Atlantic Oceans, where reported elasmobranch catch in purse seine gear was relatively low (and where required purse seine observer coverage is 5%) suggests that missing data may also be important in driving this pattern (IATTC 2019; IOTC 2019; ICCAT 2021, Table S2). In addition, set type (e.g., whether a vessel deploys a purse seine directly on a tuna school, on a FAD, or on associated dolphins) can substantially impact catch rate and therefore impact on bycatch species (Hall et al., 2013). Future research on elasmobranch catch should seek to improve and incorporate better purse seine catch data, particularly data disaggregated by set type. Additionally, better coverage of unobserved fleet fragments and regions, as well as the incorporation of indirect mortality caused by fishing gears, could help improve estimates of their impact.

The greater reported catch attributed to longline gear may also be attributed to greater distributional overlap of longline fisheries and elasmobranch habitat: 60% of the world's 7,500 tuna longline vessels are not large vessels (<24 meters in length) (Clarke et al., 2014), and thus likely fishing in coastal areas of high productivity where interaction rates with some elasmobranch species may be greater. These results point to the critical need to assess coastal artisanal fisheries using longline and gillnet gears, among others, which are largely unobserved and in many contribute to significantly high catch of vulnerable elasmobranch species (Martínez-Ortiz et al. 2015; Murua et al. 2018; Di Lorenzo et al. 2022; Lennert-Cody et al. 2022). The magnitude of elasmobranch catch in these small-scale fisheries, which were excluded from this study, is a major important gap that future research should investigate (Oliveros-Ramos et al. 2020; Lennert-Cody et al. 2022).

2.2 Commercial species

Beyond differences in gear type, we identified taxonomic patterns in reported catch that provide insight into variable fishing impacts for different species. In longline gear, for example, blue sharks comprise 83% of reported global catch. This can be attributed to two main drivers: first, while elasmobranchs are generally not primary target species of industrial tuna fleets, in some cases, tuna fishing vessels may directly or opportunistically target sharks, particularly blue, mako and porbeagle sharks (Hall & Roman 2013; Clarke et al. 2014; Juan-Jordá et al. 2017). Blue sharks are the target of fisheries in both the Indian and Atlantic Oceans, and the species dominates the international meat and fin trade, an industry valued at an $411 million in 2019 (Clarke et al. 2006; Poseidon 2022). Though stock assessments in each of these oceans have concluded that these populations are not considered overfished, there is high model uncertainty in their statuses (particularly in the Atlantic, Table 3), and there has been concern about the sustainability of ongoing high rates of exploitation and rising demand for shark meat (Dinkel & Sánchez-Lizaso 2020; Pincinato et al. 2022). One remedy tRFMOs could pursue to address commercially exploited populations that are both bycatch and target catch is to include those elasmobranchs which are targeted as 'principal species' in their Conventions (rather than only as non-target species). This would signal that they should be managed with the seriousness of target tuna and billfish. Some tRFMOs are already moving in this direction; for example, ICCAT manages mako, blue, and porbeagle sharks as target species because they are targeted by several member fleets (ICCAT 2021) and has recently adopted new convention text establishing its responsibility for pelagic elasmobranchs (ICCAT 2019). Beyond evaluating management status of these species, well-enforced and science-based management and conservation plans, improved data collection, and full traceability of shark fin and meat products are all key steps to improving the status of impacted elasmobranch populations (Simpfendorfer & Dulvy 2017; Dulvy et al. 2021).

2.3 Non-commercial species

Reported catch for other species we examined, particularly non-commercial species that are generally discarded at sea (James et al. 2016), were several orders of magnitude lower than those of blue and silky sharks. Specifically, thresher, hammerhead, oceanic whitetip, porbeagle, whale sharks, and mobulid catch was orders of magnitude lower than that of blue, mako and silky sharks. However, low relative catch cannot be conflated with low impact: it is possible that these species are infrequently caught because they are rare, poorly identified and/or not considered important for data collection; or already impacted and may be even more vulnerable than species with high catch rates.

This study also suggests that existing research may not be adequate to fully describe the threat to these rarer non-commercial species posed by tuna fishing. Our finding that only one in five of the eligible populations we examined are currently assessed, but that these assessed populations account for 95% of total catch in weight indicates that species with relatively high catch (e.g., blue, mako, and silky sharks) are prioritized for stock assessments. This is intuitive, given that managers may have more incentive to assess more economically important species which are more likely to have higher quantity and/or quality catch data. However, the lack of stock assessments for rarer species is concerning given global populations observed for all these non-commercial, less abundant species (Pacoreau et al. 2021). For example, while blue shark has been assessed conclusively in each ocean, no conclusive assessment exists in any region for hammerhead sharks, thresher sharks, or any species of mobulid, though all species are considered threatened by the IUCN Red List. For oceanic whitetip, a Critically Endangered species, a stock assessment has been conducted in only one region (Western Pacific) and suggested both historic and current overfishing (WCPFC 2019). An investigation of the status of data-poor, unassessed species is urgently needed as well as the development of improved methods for data poor species. Overall, this work points to the need to further assess to the impact of tuna fishing on pelagic elasmobranchs. Risk-based vulnerability assessments such as the recently developed EASI-Fish approach (Griffiths et al. 2019) or traditional productivity-susceptibility analyses can help prioritize species for these types of management (Hobday et al. 2011).

Still, given the wide variability in reported catch we identified across species in this study, corresponding management and conservation responses from tRFMOs should not be uniform for all species (Booth et al. 2020). For instance, species with high catch rates may be good candidates for quotas and/or total allowable bycatch limits, tools which are used to regulate management for target tunas and have recently been implemented for blue and mako sharks in ICCAT (Pons et al. 2018; ICCAT 2019b) or dynamic ocean management, an adaptative management framework that has drawn some attention in some tRFMOs (e.g. IATTC, SAC-10-INF-D). Conversely, capture for those species with relatively low but potentially impactful catch rates may benefit more from targeted precautionary measures, like pre-capture bycatch avoidance and/or post-capture life and safe release mitigation best practices (de Bruyn et al. 2013), at least until better data is available about the impact of tuna fishing on their population status.

2.4 Data constraints and improving data quality

The use of publicly reported catch data in this study dictates several caveats for interpretation, including likely biases in catch data toward higher catch reported for species that are easily identified and more abundant and more catch reported in regions and gears with better observer coverage, in addition to general underreporting of non-tuna species across all oceans (Clarke et al. 2013; Hall & Roman 2013). Importantly, there are substantial differences in the data sources we used (observer data versus logbook data, Table S1), which may have led to large differences in the quantity and quality of reported elasmobranch catch results. This underscores the need for precautionary management until data collection and reporting, as well as the derived stock assessments, can be improved. As has been demonstrated, precautionary management without full stock assessments for elasmobranchs in tRFMOs is possible—and in fact is the historic norm for elasmobranchs in tRFMOs (Cronin et al. 2022).

Beyond the need for more reported publicly available data, there are also some important taxonomic gaps in data collection identified by this study. While mobulid species represent nine of the 22 pelagic elasmobranch species examined by this study (Table 1), only two tRFMOs (ICCAT and IOTC) include mobulid rays in their publicly reported data, and this data is likely sparse given anecdotal and empirical evidence of mobulid captures in tuna purse seine fisheries (Croll et al., 2016). This is incongruous with current policy agendas in tRFMOs, all of which except ICCAT have adopted mobulid management measures in recent years, including retention bans. However, this lack of data can partially be attributed to the retention bans themselves, which may reduce the likelihood that an animal is counted as it is quickly released (though this still may result in a mortality event) (Tolotti et al. 2015). Still, the scarcity of public data on mobulid catch is alarming, given the fact that all mobulid species are experiencing population declines, and that ecological risk assessments show that they are among the most vulnerable elasmobranch species to fisheries impacts, particularly in purse seine fisheries (Ward-Paige et al. 2013; Croll et al. 2016, Duffy et al. 2019; Griffiths et al. 2019, 2021). Improved observer coverage, species identification training for observers, data collection and transparency, and inclusion in public domain data for mobulids and other non-shark pelagic elasmobranchs is a necessary first step toward meaningful conservation efforts.

Similarly, the fact the data we used were grouped at the genus, rather than species, level for thresher, hammerhead, and mako sharks as well as mobulids indicates that improving species identification for these groups is a priority. To improve identifications, observer trainings can be paired with technology like electronic monitoring and predictive artificial intelligence, both of which have recently been developed for use in tuna fisheries (van Helmond et al. 2020; Qiao et al. 2021).

In addition to incomplete data, the length-weight parameters used to convert catch data by this study are a potential source of bias, as fine-scale length frequency data was not available for every species in each gear and region, and using mean or borrowed values risks eliding the important size variability among individuals caught. Further, it is likely that spatial, temporal, and annual variation in past and current population status and dynamics, environmental and ecological conditions as well as variation in discard rate and post-capture mortality rates can significantly impact catch rate, species survival rates, and correspondingly, total mortality for a given unit of fishing effort (Lewison et al. 2009; Hutchinson et al. 2015; Escalle et al. 2016). In fact, we entirely exclude post-release mortality rates from this study—though mortality can in some cases for some species be very low, particularly for fisheries and vessels that have implemented best handling and release practices. Thus, the data we present are a coarse representation of reported catch, and not necessarily mortality. However, we suggest that the publication of a dataset of comparable public domain data is useful for future research incorporating post-release mortality rates to assess the impact of this catch on populations.

Our analyses, though hamstrung by these limitations, are most powerful for highlighting relative differences as well as the poor quality of data available to assess the impact of tuna fisheries on pelagic elasmobranchs, pointing to the need for improved data collection and reporting. Perhaps most importantly, the data gaps identified in this study points to the need for better observer coverage, data collection and reporting, and stricter enforcement of national reporting policies to tRFMOs. Further, the publication of this reported catch dataset should spur deeper investigations, including those seeking to extrapolate the potential magnitude of unreported pelagic elasmobranch catch in tuna fisheries regionally and globally. While this kind of extrapolation is outside the scope of the current study, ongoing efforts to develop tools to estimate true (e.g., reported and unreported) catch in tuna fisheries should be supported and applied to elasmobranchs (Coulter et al. 2020; Babcock et al. 2022; Gilman & Chaloupka 2022). These efforts can also aim to evaluate tRFMO public domain data in reference to other larger fisheries catch datasets like FAO Fishery Statistical Data and FIRMS Tuna Atlas and the Sea Around Us datasets. Ultimately, improved catch data can be used to identify important predictors of high elasmobranch catches, including differences in fleet and vessel behavior and seasonality, environmental conditions, fishing locations, and fishing modes that can drastically impact catch rates (Bi et al. 2021; Wang et al. 2021; Roberson & Wilcox 2022).

2.5 Management implications

The data limitations described here should not deter action and research to understand and mitigate the impacts of industrial tuna fishing on pelagic elasmobranchs; rather, they should motivate urgent improvement of data collection and submission resolution in tuna RFMOs for sharks and deeper investigation of the scope and impact of fishing on these and other non-target species. The recent commitment by IATTC and ICCAT to include sharks under their remits could be followed by other tRFMOs and for additional species, potentially affording greater attention and resources for their management and conservation. In past cases, tRFMOs and tuna fishing nations have been proactive in addressing sustainability issues for non-target species (Hall 1996; Jenkins 2007); however, they need to strengthen their efforts to help reverse elasmobranchs populations' declining trends and ensure their sustainability in the long term. When considering conservation and management measures, vessels from nations with relatively higher reported elasmobranch catch identified by this study will be important to target for implementation, enforcement, and compliance. To address the gaps and concerns identified by this study, we suggest the following immediate actions that tRFMOs and fishing nations can take:

- Improve data collection and reporting so that species-level elasmobranch catch and stock status can be adequately quantified and assessed in all tuna fisheries, which could be done through increasing human and/or electronic observer coverage (particularly in longline fisheries and small-scale/artisanal fisheries),
- Increase the number of shark stock assessed and use emerging data-poor methods (e.g. EASI-Fish), to evaluate elasmobranch populations' vulnerability on a regular basis, particularly for non-commercial threatened species; this will allow for the implementation of precautionary management until stock assessments exist,
- For overexploited and data-deficient populations, consider precautionary conservation and management measures, such as 1) limits on catches; 2) static or dynamic spatiotemporal management measures for important habitats and fishing inefficiency areas, and 3) the development of gear tools and safe handling and release best practices to reduce pre- and post-release mortality (e.g., deterrents, release devices, etc.),
- Quantify, assess, and address indirect impacts like ghost fishing and the differential effects of mitigation, conservation, and management measures on different species, and
- Improve enforcement procedures as well as monitoring, surveillance, and control systems.

Policies and mitigation measures for elasmobranchs at the tRFMO level have the potential to influence fishing over enormous ocean areas and reduce the impact of fishing by multiple fleets at once. Given the low likelihood that tuna fishing pressure on elasmobranchs will abate significantly in the immediate future (though see White & Costello 2014), tRFMOs remain uniquely positioned to implement these measures in their convention areas all over the world. This study underscores the need for tuna fisheries, tuna fishing nations, and tRFMO policymakers to take immediate and meaningful action to conserve threatened pelagic elasmobranchs.

Tables

Table 1. Pelagic elasmobranch species included in this study. All species except *P. glauca* are listed on CITES Appendix II and are reported in tRFMO capture records. Reporting level indicates the taxonomic level at which most data was available and analyzed.

Reporting level	Species	Common name	IUCN Red List Designation	Distribution
Alopias Thresher	*Alopias pelagicus*	Pelagic thresher	Endangered	Indian, Pacific
	Alopias superciliosus	Bigeye thresher	Vulnerable	Global
	Alopias vulpinus	Common thresher	Vulnerable	Global
Carcharhinus falciformis Silky shark	*Carcharhinus falciformis*	Silky shark	Vulnerable	Global
Carcharhinus longimanus Oceanic whitetip	*Carcharhinus longimanus*	Oceanic whitetip shark	Critically endangered	Global
Isurus Mako	*Isurus oxyrinchus*	Shortfin mako	Endangered	Global
	Isurus paucus	Longfin mako	Endangered	Global
Lamna nasus Porbeagle	*Lamna nasus*	Porbeagle	Vulnerable	Global
Mobulidae Mobulid	*Mobula alfredi*	Reef manta ray	Vulnerable	Indian, Western Pacific
	Mobula birostris	Oceanic manta ray	Vulnerable	Global

	Mobula eregoodoo	Longhorned pygmy devil ray	Endangered	Indian, Western Pacific
	Mobula hypostoma	Atlantic devil ray	Endangered	Atlantic
	Mobula kuhlii	Shorfin devil ray	Endangered	Indian, Western Pacific
	Mobula mobular	Spinetail devil ray	Endangered	Global
	Mobula munkiana	Munk's devil ray	Vulnerable	Eastern Pacific
	Mobula tarapacana	Sicklefin devil ray	Endangered	Global
	Mobula thurstoni	Bentfin devil ray	Endangered	Global
Prionace glauca Blue shark	*Prionace glauca*	Blue shark	Near threatened	Global
Rhincodon typus Whale shark	*Rhincodon typus*	Whale shark	Endangered	Global
Sphyrna Hammerhead	*Sphyrna lewini*	Scalloped hammerhead	Critically endangered	Global
	Sphyrna mokarran	Great hammerhead	Critically endangered	Global
	Sphyrna zygaena	Smooth hammerhead	Vulnerable	Global

Table 3. Relevant stock assessments conducted for pelagic elasmobranchs captured by longline and purse seine tuna fisheries. Stock assessments that did not determine stock status are included in this table.

RFMO	Common name	Population (if indicated)	Year Assessed	Conclusive?	Stock status	Reference	Link
IATTC	Blue shark	northern	2017	X	not overfished, overfishing not occurring	ISC 2017	http://isc.fra.go.jp/pdf/ISC17/ISC17_Annex13-Stock_Assessment_and_Future_Projections_of_Blue_Shark.pdf
IATTC	Silky	Pacific-wide	2015		undetermined	Aires-da-Silva et al, 2015	https://www.iattc.org/GetAttachment/9b8da34e-791e-4345-beba-fd6586511886/SAC-06-08b%20-%20Updated%20indicators%20for%20silky%20sharks
ICCAT	Blue shark	southern	2015	X* *high uncertainty	unlikely to be overfished / overfishing unlikely	ICCAT 2015	https://www.iccat.int/Documents/SCRS/DetRep/BSH_SA_ENG.PDF
ICCAT	Blue shark	northern	2015	X* *high uncertainty	unlikely to be overfished / overfishing unlikely	ICCAT 2015	https://www.iccat.int/Documents/SCRS/DetRep/BSH_SA_ENG.PDF
IATTC	Porbeagle	southern hemisphere	2017	X	not overfished	Hoyle et al. 2017	https://www.wcpfc.int/doc/sc13-sa-wp-12/southern-hemisphere-porbeagle-shark-assessment-placeholder
ICCAT	Porbeagle	northwest	2020	X	overfished	ICCAT 2020	https://www.iccat.int/Documents/Meetings/Docs/2020/REPORTS/2020_POR_SA_ENG.pdf
ICCAT	Porbeagle	northern and southern	2020		undetermined	ICCAT 2020	https://www.iccat.int/Documents/Meetings/Docs/2020/REPORTS/2020_POR_SA_ENG.pdf
ICCAT	Porbeagle	northeast	2009	X	overfished, overfishing	ICCAT 2009	https://www.iccat.int/Documents/Meetings/Docs/2009_POR_ASSESS_ENG.pdf
ICCAT	Porbeagle	southwest	2009	X	overfished, overfishing	ICCAT 2009	https://www.iccat.int/Documents/Meetings/Docs/2009_POR_ASSESS_ENG.pdf
ICCAT	Shortfin mako	northern	2019	X	overfished, overfishing	ICCAT 2019	https://www.iccat.int/Documents/SCRS/DetRep/SMA_SA_ENG.pdf
ICCAT	Shortfin mako	southern	2017	X	overfishing	ICCAT 2017	https://www.iccat.int/documents/meetings/docs/2017_sma_ass_rep_eng.pdf
IOTC	Porbeagle	southern hemisphere	2017	X	not overfished	Hoyle et al. 2017	https://www.wcpfc.int/doc/sc13-sa-wp-12/southern-hemisphere-porbeagle-shark-assessment-placeholder
IOTC	Shortfin mako		2018	X	overfishing occurring, not overfished	Brunel et al., 2018	http://www.iotc.org/documents/WPEB/14/37
IOTC	Silky		2018	X	overfishing, not overfished	Urbina et al, 2018	https://www.iotc.org/documents/preliminary-stock-assessment-silky-shark-indian-ocean-using-data-limited-approach
IOTC	Blue shark		2018	X	not overfished, no overfishing	IOTC, 2021	https://iotc.org/documents/SC/24/RE
WCPFC	Whale shark		2018	X	not overfished	WCPFC 2018	https://www.wcpfc.int/doc/19/whale-shark-2018
WCPFC	Blue shark	northern	2017	X	not overfished	WCPFC 2017	https://www.wcpfc.int/doc/15/north-pacific-blue-shark
WCPFC	Blue shark	southern	2017	X	overfishing unlikely	WCPFC 2017	https://www.wcpfc.int/doc/15/north-pacific-blue-shark
WCPFC	Oceanic whitetip		2019	X	overfished, overfishing	WCPFC 2019	https://www.wcpfc.int/file/361982/download?token=SeN4NxdL
WCPFC	Shortfin mako	northern	2017	X	not overfished, no overfishing	WCPFC 2019	https://www.wcpfc.int/file/361986/download?token=taiLMq8p
WCPFC	Silky		2018	X	overfishing, not overfished	WCPFC 2019	https://www.wcpfc.int/file/361983/download?token=g1tpvUEc
WCPFC	Porbeagle	southern hemisphere	2017	X	not overfished	Hoyle et al. 2017	https://www.wcpfc.int/doc/sc13-sa-wp-12/southern-hemisphere-porbeagle-shark-assessment-placeholder
WCPFC	Bigeye thresher		2016		undetermined	Fu et al 2016	https://www.wcpfc.int/doc/sc13-sa-wp-11/bigeye-thresher-shark-assessment

References

Arrizabalaga, H., Bruyn, P., Diaz, G., Murua, H., Pierre, C., Delgado, A., Gaertner, D., Ariz, J., Ruiz, J. & Kell, L. (2011). Productivity and susceptibility analysis for species caught in Atlantic tuna fisheries. *Aquatic Living Resources*, 24, 1–12.

Babcock, E.A., Harford, W.J., Gedamke, T., Soto, D. & Goodyear, C.P. (2022). *EFFICACY OF A BYCATCH ESTIMATION TOOL* (No. Collect. Vol. Sci. Pap. ICCAT, 79(5)).

Barker, M.J. & Schluessel, V. (2005). Managing global shark fisheries: suggestions for prioritizing management strategies. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 15, 325–347.

Begg, G.A., Friedland, K.D. & Pearce, J.B. (1999). Stock identification and its role in stock assessment and fisheries management: an overview. *Fisheries Research*, 43, 1–8.

Bi, R., Jiao, Y. & Browder, J.A. (2021). Climate driven spatiotemporal variations in seabird bycatch hotspots and implications for seabird bycatch mitigation. *Sci Rep*, 11, 20704.

Booth, H., Squires, D. & Milner-Gulland, E.J. (2020). The mitigation hierarchy for sharks: A risk-based framework for reconciling trade-offs between shark conservation and fisheries objectives. *Fish and Fisheries*, 21, 269–289.

Cardeñosa, D., Fields, A., Babcock, E., Zhang, H., Feldheim, K., Shea, S., Fischer, G. & Chapman, D. (2018). CITES-listed sharks remain among the top species in the contemporary fin trade. *Conservation Letters*, 11.

Clarke, S., Sato, M., Small, C., Sullivan, B., Inoue, Y. & Ochi, D. (2014). *Bycatch in Longline Fisheries for Tuna and Tuna-like Species: a Global Review of Status and Mitigation Measures*.

Clarke, S.C., Harley, S.J., Hoyle, S.D. & Rice, J.S. (2013). Population trends in Pacific Oceanic sharks and the utility of regulations on shark finning. *Conserv Biol*, 27, 197–209.

Clarke, S.C., McAllister, M.K., Milner-Gulland, E.J., Kirkwood, G.P., Michielsens, C.G.J., Agnew, D.J., Pikitch, E.K., Nakano, H. & Shivji, M.S. (2006). Global estimates of shark catches using trade records from commercial markets. *Ecology Letters*, 9, 1115–1126.

Coulter, A., Cashion, T., Cisneros-Montemayor, A.M., Popov, S., Tsui, G., Le Manach, F., Schiller, L., Palomares, M.L.D., Zeller, D. & Pauly, D. (2020). Using harmonized historical catch data to infer the expansion of global tuna fisheries. *Fisheries Research*, 221, 105379.

Croll, D.A., Dewar, H., Dulvy, N.K., Fernando, D., Francis, M.P., Galván-Magaña, F., Hall, M., Heinrichs, S., Marshall, A., Mccauley, D., Newton, K.M., Notarbartolo-Di-Sciara, G., O'Malley, M., O'Sullivan, J., Poortvliet, M., Roman, M., Stevens, G., Tershy, B.R. & White, W.T. (2016). Vulnerabilities and fisheries impacts: the uncertain future of manta and devil rays. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 26, 562–575.

Cronin, M.R., Amaral, J.E., Jackson, A.M., Jacquet, J., Seto, K.L. & Croll, D.A. (2022). Policy and transparency gaps for oceanic shark and rays in high seas tuna fisheries. *Fish and Fisheries*, 24, 56–70.

Cullis-Suzuki, S. & Pauly, D. (2010). Failing the high seas: A global evaluation of regional fisheries management organizations. *Marine Policy*, 34, 1036–1042.

Curran, D. & Bigelow, K. (2016). *Length – Weight Relationships for 73 Species and Species Groups as Reported in the 2011–2013 National Bycatch Reports for Pelagic Longline Fisheries in Hawaii and American Samoa* (PIFSC Data Report No. DR-16-004).

Davies, R.W.D., Cripps, S.J., Nickson, A. & Porter, G. (2009). Defining and estimating global marine fisheries bycatch. *Marine Policy*, 33, 661–672.

Dent, F. & Clarke, S. (2015). State of the global market for shark products. *FAO Fisheries and Aquaculture Technical Paper (FAO) eng no. 590*.

Di Lorenzo, M., Calò, A., Di Franco, A., Milisenda, G., Aglieri, G., Cattano, C., Milazzo, M. & Guidetti, P. (2022). Small-scale fisheries catch more threatened elasmobranchs inside partially protected areas than in unprotected areas. *Nat Commun*, 13, 4381.

Dinkel, T.M. & Sánchez-Lizaso, J.L. (2020). Involving stakeholders in the evaluation of management strategies for shortfin mako (Isurus oxyrinchus) and blue shark (Prionace glauca) in the Spanish longline fisheries operating in the Atlantic Ocean. *Marine Policy*, 120, 104124.

Dulvy, N.K., Baum, J.K., Clarke, S., Compagno, L.J.V., Cortés, E., Domingo, A., Fordham, S., Fowler, S., Francis, M.P., Gibson, C., Martínez, J., Musick, J.A., Soldo, A., Stevens, J.D. & Valenti, S. (2008). You can swim but you can't hide: the global status and conservation of oceanic pelagic sharks and rays. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 18, 459–482.

Dulvy, N.K., Pacoureau, N., Rigby, C.L., Pollom, R.A., Jabado, R.W., Ebert, D.A., Finucci, B., Pollock, C.M., Cheok, J., Derrick, D.H., Herman, K.B., Sherman, C.S., VanderWright, W.J., Lawson, J.M., Walls, R.H.L., Carlson, J.K., Charvet, P., Bineesh, K.K., Fernando, D., Ralph, G.M., Matsushiba, J.H., Hilton-Taylor, C., Fordham, S.V. & Simpfendorfer, C.A. (2021). Overfishing drives over one-third of all sharks and rays toward a global extinction crisis. *Current Biology*, 31, 4773-4787.e8.

Escalle, L., Pennino, M.G., Gaertner, D., Chavance, P., Delgado de Molina, A., Demarcq, H., Romanov, E. & Merigot, B. (2016). Environmental factors and megafauna spatio-temporal co-occurrence with purse-seine fisheries. *Fisheries Oceanography*, 25, 433–447.

FAO. (2020). *The State of Food and Agriculture 2020: Overcoming water challenges in agriculture* (No. 978-92-5-133441–6). FAO, Rome, Italy.

Ferretti, F., Worm, B., Britten, G.L., Heithaus, M.R. & Lotze, H.K. (2010). Patterns and ecosystem consequences of shark declines in the ocean: Ecosystem consequences of shark declines. *Ecology Letters*, no-no.

Filmalter, J., Capello, M., Deneubourg, J.-L., Cowley, P. & Dagorn, L. (2013). Looking behind the curtain: Quantifying massive shark mortality in fish aggregating devices. *Frontiers in Ecology and the Environment*, 11, 291–296.

Fowler, S., Bräutigam, A., Okes, N. & Sant, G. (2021). *Conservation, Fisheries, Trade and Management Status of CITES-Listed Sharks* (No. BfN-Skripten 607). Bundesamt für Naturschutz (BfN) Federal Agency for Nature Conservation.

Germanov, E.S., Marshall, A.D., Bejder, L., Fossi, M.C. & Loneragan, N.R. (2018). Microplastics: No Small Problem for Filter-Feeding Megafauna. *Trends Ecol Evol*, 33, 227–232.

Gilman, E. & Chaloupka, M. (2022). Applying a sequential evidence hierarchy, with caveats, to support prudent fisheries bycatch policy. *Reviews in Fish Biology and Fisheries*.

Gilman, E., Clarke, S., Brothers, N., Alfaro-Shigueto, J., Mandelman, J., Mangel, J., Petersen, S., Piovano, S., Thomson, N., Dalzell, P., Donoso, M., Goren, M. & Werner, T. (2008). Shark interactions in pelagic longline fisheries. *Marine Policy*, 32, 1–18.

Gilman, E.L. (2011). Bycatch governance and best practice mitigation technology in global tuna fisheries. *Marine Policy*, 35, 590–609.

Griffiths, S.P., Kesner-Reyes, K., Garilao, C., Duffy, L.M. & Román, M.H. (2019). Ecological Assessment of the Sustainable Impacts of Fisheries (EASI-Fish): a flexible vulnerability assessment approach to quantify the cumulative impacts of fishing in data-limited settings. *Marine Ecology Progress Series*, 625, 89–113.

Hall, M. & Roman, M. (2013). *Bycatches and non-tuna catches in the tropical tuna purse seine fisheries of the world* (FAO Fisheries and Aquaculture Technical Paper No. 9789251072417).

Hall, M.A. (1996). On bycatches. *Reviews in Fish Biology and Fisheries*, 6, 319–352.

Healy, T.J., Hill, N.J., Barnett, A. & Chin, A. (2020). A global review of elasmobranch tourism activities, management and risk. *Marine Policy*, 118, 103964.

Heidrich, K.N., Juan-Jordá, M.J., Murua, H., Thompson, C.D.H., Meeuwig, J.J. & Zeller, D. (2022). Assessing progress in data reporting by tuna Regional Fisheries Management Organizations. *Fish and Fisheries*, n/a.

van Helmond, A.T.M., Mortensen, L.O., Plet-Hansen, K.S., Ulrich, C., Needle, C.L., Oesterwind, D., Kindt-Larsen, L., Catchpole, T., Mangi, S., Zimmermann, C., Olesen, H.J., Bailey, N., Bergsson, H., Dalskov, J., Elson, J., Hosken, M., Peterson, L., McElderry, H., Ruiz, J., Pierre, J.P., Dykstra, C. & Poos, J.J. (2020). Electronic monitoring in fisheries: Lessons from global experiences and future opportunities. *Fish and Fisheries*, 21, 162–189.

Heupel, M.R., Knip, D.M., Simpfendorfer, C.A. & Dulvy, N.K. (2014). Sizing up the ecological role of sharks as predators. *Marine Ecology Progress Series*, 495, 291–298.

Hobday, A.J., Smith, A.D.M., Stobutzki, I.C., Bulman, C., Daley, R., Dambacher, J.M., Deng, R.A., Dowdney, J., Fuller, M., Furlani, D., Griffiths, S.P., Johnson, D., Kenyon, R., Knuckey, I.A., Ling, S.D., Pitcher, R., Sainsbury, K.J., Sporcic, M., Smith, T., Turnbull, C., Walker, T.I., Wayte, S.E., Webb, H., Williams, A., Wise, B.S. & Zhou, S. (2011). Ecological risk assessment for the effects of fishing. *Fisheries Research*, 108, 372–384.

Hutchinson, M. (2021). Quantitative estimates of post-release survival rates of sharks captured in Pacific tuna longline fisheries reveal handling and discard practices that improve survivorship.

Hutchinson, M.R., Itano, D.G., Muir, J.A. & Holland, K.N. (2015). Post-release survival of juvenile silky sharks captured in a tropical tuna purse seine fishery. *Marine Ecology Progress Series*, 521, 143–154.

IOTC. (2011). *Resolution 11/04 on a Regional Observer Scheme. | InforMEA*.

James, K.C., Lewison, R.L., Dillingham, P.W., Curtis, K.A. & Moore, J.E. (2016). Drivers of retention and discards of elasmobranch non-target catch. *Environmental Conservation*, 43, 3–12.

Jenkins, L.D. (2007). Bycatch: interactional expertise, dolphins and the US tuna fishery. *Studies in History and Philosophy of Science Part A*, 38, 698–712.

Jorgensen, S.J., Micheli, F., White, T.D., Houtan, K.S.V., Alfaro-Shigueto, J., Andrzejaczek, S., Arnoldi, N.S., Baum, J.K., Block, B., Britten, G.L., Butner, C., Caballero, S., Cardeñosa, D., Chapple, T.K., Clarke, S., Cortés, E., Dulvy, N.K., Fowler, S., Gallagher, A.J., Gilman, E., Godley, B.J., Graham, R.T., Hammerschlag, N., Harry, A.V., Heithaus, M.R., Hutchinson, M., Huveneers, C., Lowe, C.G., Lucifora, L.O., MacKeracher, T., Mangel, J.C., Martins, A.P.B., McCauley, D.J., McClenachan, L., Mull, C., Natanson, L.J., Pauly, D., Pazmiño, D.A., Pistevos, J.C.A., Queiroz, N., Roff, G., Shea, B.D., Simpfendorfer, C.A., Sims, D.W., Ward-Paige, C., Worm, B. & Ferretti, F. (2022). Emergent research and priorities for shark and ray conservation. *Endangered Species Research*, 47, 171–203.

Juan-Jordá, M.J., Murua, H., Arrizabalaga, H., Dulvy, N.K. & Restrepo, V. (2018). Report card on ecosystem-based fisheries management in tuna regional fisheries management organizations. *Fish and Fisheries*, 19, 321–339.

Juan-Jordá, M.J., Murua, H., Arrizabalaga, H., Merino, G., Pacoureau, N. & Dulvy, N.K. (2022). Seventy years of tunas, billfishes, and sharks as sentinels of global ocean health. *Science*, 378, eabj0211.

Lawson, J.M., Fordham, S.V., O'Malley, M.P., Davidson, L.N.K., Walls, R.H.L., Heupel, M.R., Stevens, G., Fernando, D., Budziak, A., Simpfendorfer, C.A., Ender, I., Francis, M.P., Notarbartolo di Sciara, G. & Dulvy, N.K. (2017). Sympathy for the devil: a conservation strategy for devil and manta rays. *PeerJ*, 5, e3027.

Leeney, R.H. & Poncelet, P. (2015). Using fishers' ecological knowledge to assess the status and cultural importance of sawfish in Guinea-Bissau. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 25, 411–430.

Lennert-Cody, C.E., McCracken, M., Siu, S., Oliveros-Ramos, R., Maunder, M.N., Aires-da-Silva, A., Carvajal-Rodríguez, J.M., Opsomer, J.D. & de Barros, P. (2022). Single-cluster systematic sampling designs for shark catch size composition in a Central American longline fishery. *Fisheries Research*, 251, 106320.

Lewison, R.L., Soykan, C.U. & Franklin, J. (2009). Mapping the bycatch seascape: multispecies and multi-scale spatial patterns of fisheries bycatch. *Ecological Applications*, 19, 920–930.

Martínez-Ortiz, J., Aires-da-Silva, A.M., Lennert-Cody, C.E. & Maunder, M.N. (2015). The Ecuadorian Artisanal Fishery for Large Pelagics: Species Composition and Spatio-Temporal Dynamics. *PLoS ONE*, 10, e0135136.

Molina, J. & Cooke, S. (2012). Trends in shark bycatch research: Current status and research needs. *Reviews in Fish Biology and Fisheries*, 22, 719–737.

Moreno, G., Murua, J. & Restrepo, V. (2018). The use of non-entangling FADs to reduce ghost fishing.

Mucientes, G., Vedor, M., Sims, D.W. & Queiroz, N. (2022). Unreported discards of internationally protected pelagic sharks in a global fishing hotspot are potentially large. *Biological Conservation*, 269, 109534.

Murua, H., Griffiths, S., Hobday, A., Clarke, S., Cortés, E., Gilman, E., Santiago, J., Arrizabalaga, H., Bruyn, P., Lopez, J., Aires-da-Silva, A. & Restrepo, V. (2021). Shark mortality cannot be assessed by fishery overlap alone. *Nature*, 595, E4–E7.

Murua, H., Semba, Y., Báez, J.C., Santiago, J., Coelho, R., Zudaire, I., Neves, C., Rosa, D., Bach, P., Arrizabalaga, H., Ramos, M.L., Zhu, J.F. & Ruiz, J. (2018). *Updated Ecological Risk Assessment (ERA) for shark species caught in fisheries managed by the Indian Ocean Tuna Commission (IOTC)* (No. IOTC-2018-SC21-14_Rev1). IOTC.

Murua, H., Zudaire, I., Tolotti, M., Murua, J., Capello, M., Basurko, O.C., Krug, I., Grande, M., Arregui, I., Uranga, J., Ferarios, J.M., Sabarros, P., Ruiz, J., Baidai, Y., Ramos, M.L., Báez, J.C., Abascal, F., Arrizabalaga, H., Moreno, G., Dagorn, L. & Santiago, J. (2023). Lessons learnt from the first large-scale biodegradable FAD research experiment to mitigate drifting FADs impacts on the ecosystem. *Marine Policy*, 148, 105394.

Musyl, M.K. & Gilman, E.L. (2019). Meta-analysis of post-release fishing mortality in apex predatory pelagic sharks and white marlin. *Fish and Fisheries*, 20, 466–500.

Oliver, S., Braccini, M., Newman, S.J. & Harvey, E.S. (2015). Global patterns in the bycatch of sharks and rays. *Marine Policy*, 54, 86–97.

Oliveros-Ramos, R., Lennert-Cody, C.E., Siu, S., Salaverría, S., Maunder, M., Aires-da-Silva, A. & Carvajal Rodríguez, J. (2020). Pilot study for a shark fishery sampling program in Central America.

Pacoureau, N., Rigby, C.L., Kyne, P.M., Sherley, R.B., Winker, H., Carlson, J.K., Fordham, S.V., Barreto, R., Fernando, D., Francis, M.P., Jabado, R.W., Herman, K.B., Liu, K.-M., Marshall, A.D., Pollom, R.A., Romanov, E.V., Simpfendorfer, C.A., Yin, J.S., Kindsvater, H.K. & Dulvy, N.K. (2021). Half a century of global decline in oceanic sharks and rays. *Nature*, 589, 567–571.

Pincinato, R.B.M., Gasalla, M.A., Garlock, T. & Anderson, J.L. (2022). Market incentives for shark fisheries. *Marine Policy*, 139, 105031.

Poseidon. (2022). Blue Shark: Economic valuation of the global market for blue shark products and interdependent policy analysis for sustainable management and trade.

Qiao, M., Wang, D., Tuck, G.N., Little, L.R., Punt, A.E. & Gerner, M. (2021). Deep learning methods applied to electronic monitoring data: automated catch event detection for longline fishing. *ICES Journal of Marine Science*, 78, 25–35.

Queiroz, N., Humphries, N.E., Couto, A., Vedor, M., da Costa, I., Sequeira, A.M.M., Mucientes, G., Santos, A.M., Abascal, F.J., Abercrombie, D.L., Abrantes, K., Acuña-Marrero, D., Afonso, A.S., Afonso, P., Anders, D., Araujo, G., Arauz, R., Bach, P., Barnett, A., Bernal, D., Berumen, M.L., Bessudo Lion, S., Bezerra, N.P.A., Blaison, A.V., Block, B.A., Bond, M.E., Bonfil, R., Bradford, R.W., Braun, C.D., Brooks, E.J., Brooks, A., Brown, J., Bruce, B.D., Byrne, M.E., Campana, S.E., Carlisle, A.B., Chapman, D.D., Chapple, T.K., Chisholm, J., Clarke, C.R., Clua, E.G., Cochran, J.E.M., Crochelet, E.C., Dagorn, L., Daly, R., Cortés, D.D., Doyle, T.K., Drew, M., Duffy, C.A.J., Erikson, T., Espinoza, E., Ferreira, L.C., Ferretti, F., Filmalter, J.D., Fischer, G.C., Fitzpatrick, R., Fontes, J., Forget, F., Fowler, M., Francis, M.P., Gallagher, A.J., Gennari, E., Goldsworthy, S.D., Gollock, M.J., Green, J.R., Gustafson, J.A., Guttridge, T.L., Guzman, H.M., Hammerschlag, N., Harman, L., Hazin, F.H.V., Heard, M., Hearn, A.R., Holdsworth, J.C., Holmes, B.J., Howey, L.A., Hoyos, M., Hueter, R.E., Hussey, N.E., Huveneers, C., Irion, D.T., Jacoby, D.M.P., Jewell, O.J.D., Johnson, R., Jordan, L.K.B., Jorgensen, S.J., Joyce, W., Keating Daly, C.A., Ketchum, J.T., Klimley, A.P., Kock, A.A., Koen, P., Ladino, F., Lana, F.O., Lea, J.S.E., Llewellyn, F., Lyon, W.S., MacDonnell, A., Macena, B.C.L., Marshall, H., McAllister, J.D., McAuley, R., Meÿer, M.A., Morris, J.J., Nelson, E.R., Papastamatiou, Y.P., Patterson, T.A., Peñaherrera-Palma, C., Pepperell, J.G., Pierce, S.J., Poisson, F., Quintero, L.M., Richardson, A.J., Rogers, P.J., Rohner, C.A., Rowat, D.R.L., Samoilys, M., Semmens, J.M., Sheaves, M., Shillinger, G., Shivji, M., Singh, S., Skomal, G.B., Smale, M.J., Snyders, L.B., Soler, G., Soria, M., Stehfest, K.M., Stevens, J.D., Thorrold, S.R., Tolotti, M.T., Towner, A., Travassos, P., Tyminski, J.P., Vandeperre, F., Vaudo, J.J., Watanabe, Y.Y., Weber, S.B., Wetherbee, B.M., White, T.D., Williams, S., Zárate, P.M., Harcourt, R., Hays, G.C., Meekan, M.G., Thums, M., Irigoien, X., Eguiluz, V.M., Duarte, C.M., Sousa, L.L., Simpson, S.J., Southall, E.J. & Sims, D.W. (2019). Global spatial risk assessment of sharks under the footprint of fisheries. *Nature*, 572, 461–466.

Roberson, L.A. & Wilcox, C. (2022). Bycatch rates in fisheries largely driven by variation in individual vessel behaviour. *Nat Sustain*, 1–9.

Simpfendorfer, C.A. & Dulvy, N.K. (2017). Bright spots of sustainable shark fishing. *Current Biology*, 27, R97–R98.

Sims, D.W. & Queiroz, N. (2016). Unlimited by-catch limits recovery. *Nature*, 531, 448–448.

Stevens, J. (2000). The effects of fishing on sharks, rays, and chimaeras (chondrichthyans), and the implications for marine ecosystems. *ICES Journal of Marine Science*, 57, 476–494.

Tolotti, M.T., Filmalter, J.D., Bach, P., Travassos, P., Seret, B. & Dagorn, L. (2015). Banning is not enough: The complexities of oceanic shark management by tuna regional fisheries management organizations. *Global Ecology and Conservation*, 4, 1–7.

Vincent, A.C.J., Sadovy de Mitcheson, Y.J., Fowler, S.L. & Lieberman, S. (2014). The role of CITES in the conservation of marine fishes subject to international trade. *Fish Fish*, 15, 563–592.

Wang, J., Gao, C., Wu, F., Gao, X., Chen, J., Dai, X., Tian, S. & Chen, Y. (2021). The discards and bycatch of Chinese tuna longline fleets in the Pacific Ocean from 2010 to 2018. *Biological Conservation*, 255, 109011.

WCPFC. (2021). CONSERVATION AND MANAGEMENT MEASURE FOR BIGEYE, YELLOWFIN AND SKIPJACK TUNA IN THE WESTERN AND CENTRAL PACIFIC OCEAN.

White, C. & Costello, C. (2014). Close The High Seas To Fishing? *Plos Biol.*, 12, E1001826.

White, T.D., Ferretti, F., Kroodsma, D.A., Hazen, E.L., Carlisle, A.B., Scales, K.L., Bograd, S.J. & Block, B.A. (2019). Predicted Hotspots Of Overlap Between Highly Migratory Fishes And Industrial Fishing Fleets In The Northeast Pacific. *Sci. Adv.*

Williams, P., Smith, N., Tuiloma, I., Falasi, C. & Clarke, S. (2016). *Trial Application of the BDEP Template for Summarizing Bycatch Data | SC12-EB-WP-12*.

Worm, B., Davis, B., Kettemer, L., Ward-Paige, C.A., Chapman, D., Heithaus, M.R., Kessel, S.T. & Gruber, S.H. (2013). Global Catches, Exploitation Rates, And Rebuilding Options For Sharks. *Mar. Policy*.

Worm, B., Hilborn, R., Baum, J.K., Branch, T.A., Collie, J.S., Costello, C., Fogarty, M.J., Fulton, E.A., Hutchings, J.A., Jennings, S., Jensen, O.P., Lotze, H.K., Mace, P.M., Mcclanahan, T.R., Minto, C., Palumbi, S.R., Parma, A.M., Ricard, D., Rosenberg, A.A., Watson, R. & Zeller, D. (2009). Rebuilding Global Fisheries. *Science (80-.).*

Yokoi, H., Ijima, H., Ohshimo, S. & Yokawa, K. (2017). Impact Of Biology Knowledge On The Conservation And Management Of Large Pelagic Sharks. *Sci. Reports 2017 71*, 7, 1–14.