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Review

Global manta and devil ray population declines: Closing policy and management gaps to reduce fisheries mortality

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ABSTRACT

Significant progress has been made in advancing priority actions to conserve manta and devil rays, yet implementation and enforcement of protective measures often fall short, leaving most mobulid populations at risk of overfishing. Drawing on a literature review, fisheries databases, agency reports, and expert interviews, we assess global trends in mobulid catch and mortality. We examine both targeted and incidental catch, in small (<15 m, 'SV') and large (>15 m, 'LV') vessel fisheries to identify hotspots with the highest risk of fisheries-related mortality and population decline. We estimate global fisheries catch at 264,520 (184,407–344,987) mobulids per year, with SV fisheries accounting for 87 % of global mortality. The highest-risk hotspots, based on mortality and declines, are located in India, Indonesia, Sri Lanka, Peru, and Myanmar. Mobulid retention is driven by demand, with higher mortality rates observed in countries exporting gill plates, and to a lesser extent, in those trading meat domestically or internationally. We recommend urgent implementation and enforcement of mobulid listings under the Convention on International Trade in Endangered Wild Flora and Fauna (CITES), the Convention on the Conservation of Migratory Species of Wild Animals (CMS), and national protective measures, including (i) uplisting mobulids to CITES Appendix I, (ii) full legislative protection for all mobulid species in high-risk fishing nations to reduce demand, (iii) avoiding fishing in critical habitats through permanent or temporary targeted area closures, or management, (iv) limiting drift gillnet effort, and (v) involving fishers in management decisions and implementation.

1. Introduction

Biodiversity loss across terrestrial and aquatic environments, driven by human activities, has reached unprecedented levels (Díaz et al., 2019; Díaz and Malhi, 2022). With the increase of global fishing effort and the modernisation of fishing fleets, 35.5 % of fish stocks are overfished (Sharma et al., 2025) and many stocks and species are threatened with extinction (Pauly et al., 1998; Costello et al., 2012). Along with rising fishing pressure, high market prices for shark and ray products, such as fins, meat, and gill plates, have led to a stark decline in their abundance over the past 50 years (Pacoureau et al., 2021; Dulvy et al., 2021; Juan-Jordá et al., 2022; Dulvy et al., 2024).

Manta and devil rays (genus *Mobula*, hereafter referred to as mobulids), a group of nine (and one putative) species found in warm and temperate waters circumglobally, are among the most threatened elasmobranchs (Notarbartolo di Sciara et al., 2019; Hosegood et al., 2020; Dulvy et al., 2021). Although formal stock assessments are lacking, they are considered overfished in many parts of their geographical ranges (Lewis et al., 2015; Fernando and Stewart, 2021; Moazzam, 2018; Venables et al., 2025; Laglbauer et al., 2025). Their intrinsic life-history characteristics (including low reproductive rates and late maturity) preclude even low levels of fisheries captures if populations are to be maintained (Notarbartolo di Sciara, 1988; Marshall and Bennett, 2010; Pardo et al., 2016; Dulvy et al., 2017; Stewart et al., 2018; Barrowclift et al., 2025). Rising demand for derivative products incentivises many fishers, who once considered mobulids a low-value incidental catch, to increasingly retain or target them (Dewar, 2002; Croll et al., 2016; O'Malley et al., 2017; Hau and Shea, 2023). Domestic consumption and international trade of their meat and gill plates drive targeted fisheries and retention of incidental catch (Palacios et al., 2025).

Mobulids inhabit the same productive pelagic waters as many teleosts targeted by fisheries and are frequently caught incidentally across coastal and offshore operations using diverse, often non-selective, gear types (Ward-Paige et al., 2013; Croll et al., 2016). They represent a significant component of bycatch in small-vessel (SV; ≤15 m in length) mixed-species fisheries (Fernando and Stewart, 2021; Rojas-Perea et al., 2025), some of which operate offshore, in areas beyond national jurisdictions (ABNJ) (Fernando and Stewart, 2021). Mobulids are also caught by large-vessel (LV; >15 m in length) fisheries, where mortality can arise from interaction with gear, retention, or poor handling practices (Hall and Roman, 2013; Lezama-Ochoa et al., 2019; Stewart et al., 2024). Additionally, despite multiple studies quantifying mobulid fisheries at local or regional scales, or within specific global fleets (Couturier et al., 2012; Croll et al., 2016; Lawson et al., 2017), a lack of quantitative, comparative information limits capacity to identify catch and mortality hotspots for mobulids (Stewart et al., 2018). This knowledge gap is especially relevant given the scale of global mobulid catch, which appears to be concentrated in certain locations. For example, between 2011 and 2020, mobulid landings in Sri Lankan SV fisheries were estimated at >51,000 individuals/year (Fernando and Stewart, 2021). These figures vastly exceed previous global estimates of 13,000 individuals bycaught annually (1993–2013) in LV tropical tuna purse seine fisheries, despite data gaps and declining catch trends since then (Croll et al., 2016; Lezama-Ochoa et al., 2019). Moreover, the context of SV and LV fisheries tend to differ widely. Mobulids are often retained by SV because demand for meat and gills provides additional economic and food security benefits to fishers. On the contrary, they are usually discarded from LV fisheries (Croll et al., 2016; Alfaro-Cordova et al., 2017; Lezama-Ochoa et al., 2019; Haque et al., 2021), with post-release survival ranging widely, from 20 to 74 % (Stewart et al., 2024).

To reduce the impact of fisheries and regulate international trade, mobulids have been included in several multilateral environmental agreements (Lawson et al., 2017). All species are listed on Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), which requires international trade in mobulid products among the 185 Parties and landings of catches from ABNJ to be legal, traceable, and non-detrimental to the species' survival in the wild (CITES, 2016). Mobulids are also listed on Appendix I of the Convention on the Conservation of Migratory Species of Wild Animals (CMS), which requires the 133 Parties to strictly protect them, including prohibiting their catch and retention, and preserving their habitat, as well as listing on CMS Appendix II, which encourages Parties to cooperate over their management (Lawson and Fordham, 2018). Furthermore, a listing on the CMS Sharks Memorandum of Understanding (Sharks MOU) aims to facilitate cooperation between 64 Signatories (including some non-Parties to CMS) on conservation measures. Finally, all major tuna Regional Fisheries Management Organisations (tRFMOs), which are responsible for the management of tuna and billfish fisheries, have retention bans and best-practice guidelines for safe handling and release of mobulids (Hutchinson et al., 2020; Cronin et al., 2023). Overall, however, the effectiveness of these regulatory instruments has been questionable (White et al., 2018; Lawson and Fordham, 2018) because they rely on member countries implementing and enforcing environmental, fishing and trade regulations, and compliance has often been low (MacNeil et al., 2020; Pacoureau et al., 2021; Booth et al., 2022).

Identifying appropriate domestic management and compliance measures to curb fisheries threats requires standardisation of best-available data to enable informed decision-making (Stewart et al., 2024; Palacios et al., 2025). To identify priority actions for reducing mobulid mortality across global SV and LV fisheries, we (i) review existing domestic and international policies for mobulids, (ii) examine trends in mobulid catch and mortality to identify hotspots, and (iii) assess potential factors associated with higher fisheries-related mortality globally (i.e. regulatory frameworks and domestic and international demand for mobulid meat and gill plates), to uncover potential gaps in policy, enforcement, and management strategies.

2. Materials and methods

This study used a multi-source, mixed methods approach to describe global mobulid fisheries, threats, and regulatory frameworks. We began with a literature review to clarify definitions of fishing sectors to categorize mobulid catch across SV and LV fisheries. We drew on documentation from the Food and Agriculture Organisation of the United Nations (FAO), tRFMOs, Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), Marine Stewardship Council (MSC), and International Seafood Sustainability Foundation (ISSF), and country-specific case studies (SI1).

Country-focused surveys and expert interviews provided additional data on fisheries, legislation, trade, and conservation priorities (Fig. 1; SI_Doc1; Palacios et al., 2025). Ethical approval was obtained from the relevant Research Compliance Administration (ORCA) (IRB number HS-FY2023-179) and followed the European General Data Protection Regulation ("GDPR"). Briefly, between November 2023 and April 2025, experts and country contacts were identified through the IUCN Shark Specialist Group (iucnssg.org), The Manta Trust research affiliate network (research.mantatrust.org), and authors of relevant peer-reviewed literature. A total of 178 experts across 112 countries (mobulid range states) were contacted via email and defined as stakeholders from academic, governmental or non-governmental organisations with expertise in elasmobranch fisheries (where possible mobulid fisheries) to answer online surveys hosted on Qualtrics. A snowball technique was used to identify additional relevant stakeholders (Parker et al., 2019). This resulted in 111 respondents from 71 countries in online surveys, of which 21 also participated in follow-up interviews.

National regulations were identified via expert interviews and online searches and cross-referenced with legal documents (e.g., government Gazettes, statutes, and regulatory orders), and classified into three categories (SI4): (i) shark and ray sanctuaries, (ii) protecting all mobulids in the Exclusive Economic Zone (EEZ), and (iii) protecting only some mobulid species found in the EEZ (i.e., ranging from one to three species). Countries that are Parties to international agreements with *Decisions* or *Resolutions* in place relevant to the protection of mobulids were identified, including CMS and/or the Bern, Barcelona, or Cartagena Conventions, and tRFMOs.

Global catch, and mortality (combined landings and at-vessel mortality, 'AVM') data were compiled from peer-reviewed articles, reports, and grey literature, with 18 variables used for global landing estimates (SI2, 3). Post-release mortality was not considered due to a lack of data for most gears and fleets (Stewart et al., 2024). Official and agency data sources included FAO FishStatJ (1997–2023) (FAO, 2024, SI5); tRFMO public databases, such as the International Commission for the Conservation of Atlantic Tuna (ICCAT) and the Indian Ocean Tuna Commission (IOTC) (ICCAT, 2024; IOTC, 2024; SI6), tRFMO reports for the Western and Central Pacific Fisheries Commission (WCPFC, Tremblay-Boyer and Berkenbusch, 2020), or literature citing tRFMO data, e.g., the Inter-American Tropical Tuna Commission (IATTC, in Lezama-Ochoa et al., 2019); the Gulf States Marine Fisheries Commission Southeast Area Monitoring & Assessment Program South Atlantic Coastal Trawl Survey (SEAMAP, 2022), a Non-Detriment Findings document (NDF, Thomas et al., 2022), and the Sea Around Us Project (SAUP 2012–2018; Worm et al., 2024) (Fig. 1). Mobulid catch/landing and population declines were extracted from published estimates or estimated using catch/landings records and diver surveys corrected for dive effort. The analytical approaches included decline calculations from peak catch year to the end year of a given dataset, interval comparisons, effort-standardised metrics, and modeled estimates, where possible (SI7). For SEAMAP data off southeastern USA, *M. hypostoma* catches per trawl were used to estimate trends in Catch per Unit Effort (CPUE) (Boggio-Pasqua et al., 2025 [In review]). Where CPUE in catch per set was not available, such as in Peru, Landings Per Registered Vessel (LPRV) combined landing data with vessel registries (i.e., IMPARPE; De la Puente et al., 2020), using projections in registered vessels to address data gaps (e.g., 2019–2023 vessel estimates) (Rojas-Perea et al., 2025). To estimate the rate of decline over time, we used a Poisson generalised linear model (GLM) to assess whether mobulid standardised decline rates (the ratio of reported declines in percentage, divided by the period over which the decline was observed) increased over time. To do this, we tested the effect of the year of first observation on the magnitude of standardised decline rates. We hypothesised that the later the observation year, the greater the magnitude of the standardised decline rates. Where mobulid catches were recorded in weight (tons or kg) in published literature or official data, quantities were converted to counts (number of individuals) based on the average weights estimated from a

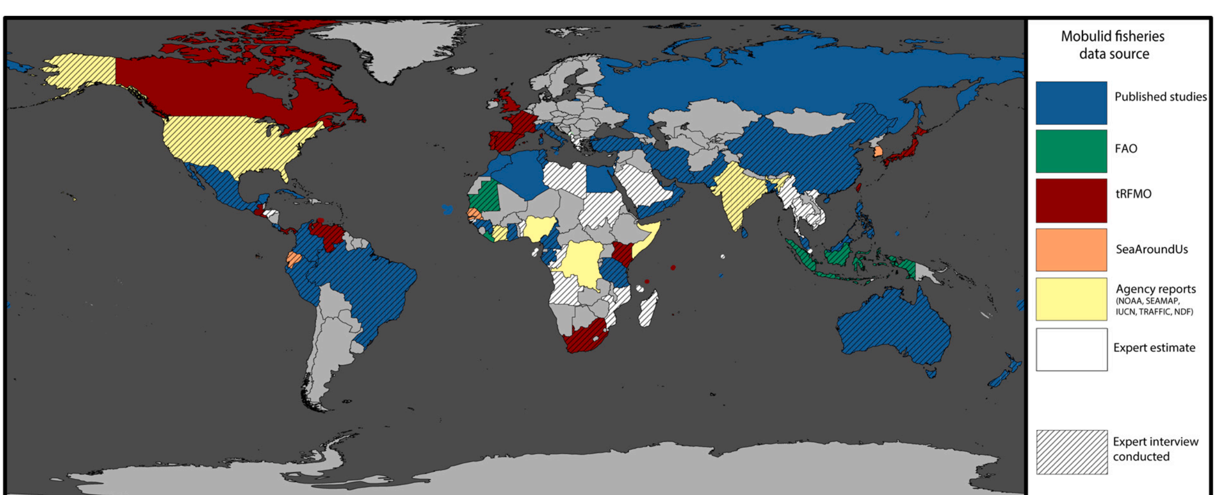

Fig. 1. Mobulid fisheries data sources used to assess catch estimates for this study. Countries for which expert interviews were conducted are indicated by diagonal dashes. The main data source is highlighted where multiple data sources were available for a given country. For countries with only expert interview data, some provided catch estimates while others did not.

species-specific review of caught/landed specimens (SI8; SI_Doc1; D'Costa et al., 2025 [In review]).

Based on expert elicitation and data in the literature, key variables were explored to assess mobulid catch and mortality across countries and fleets. These included fishing areas, vessel sizes/types, fishing methods (gear, retention practices, AVM), fishery type, socio-economic context (domestic and international meat and/or gill plate trade) and regulatory context (SI2 & SI3). Priority threats were identified by synthesizing catch data, expert input, and literature to highlight high mortality rates and country/region specific decline estimates across different fishery types, and trade and policy frameworks. Fisheries were categorized in terms of two scenarios: a) whether the catch was all or partially incidental or targeted, and b) whether the catch was all or partially retained or discarded (Croll et al., 2016; Lawson et al., 2017). This resulted in four categories: (1) all incidental; all discarded ('discarded incidental catch'), (2) all incidental; some retained and some discarded ('retained and discarded incidental catch'), (3) some targeted and some incidental; some retained and some discarded ('retained and discarded incidental catch'), and (4) some targeted and some incidental; all retained ('retained incidental catch and targeted catch'). Key factors influencing total fisheries mortality (the sum of SV landings and LV retention and AVM) were assessed using a Bayesian generalised linear model (SI9). Variables included in the analysis were: Human Development Index (HDI, quantitative, 0 to 1), mobulid trade context of the country (exporting gill plates, or using meat domestically), primary gear type in which mobulids are caught (drift gillnet, set gillnet, longline, purse seine, trawl net, and unknown, included as fixed effects with drift gillnets fit as the intercept), policy context ('All mobulid protected in

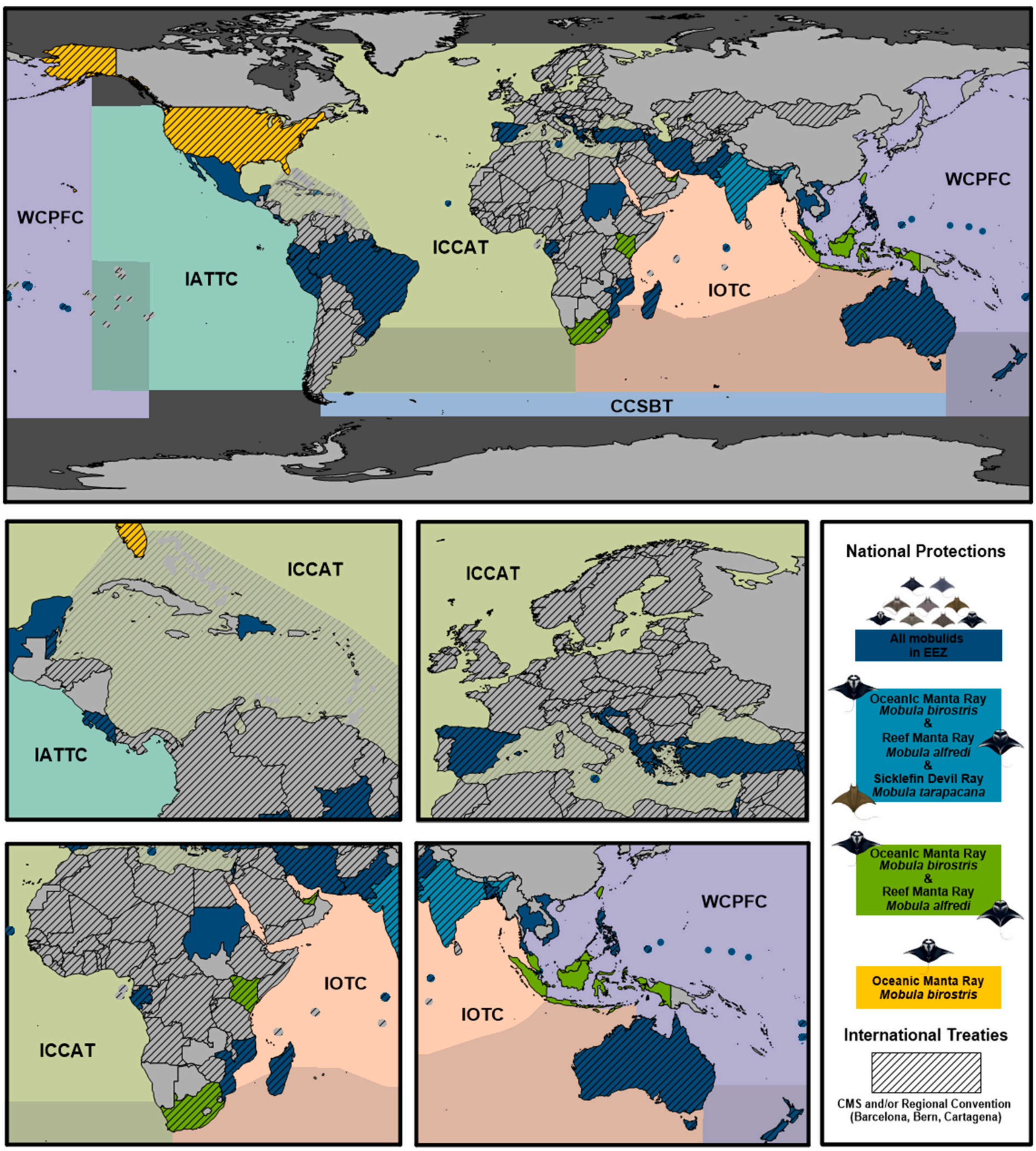

Fig. 2. National and international protections for mobulids globally. International agreements to protect mobulids are grouped (diagonal lines) (SI4, 10).

EEZ', 'Some mobulid protected in EEZ', 'Shark & Ray sanctuary', 'International protection only', 'tRFMO protection only', or 'No Protection', which was fit as the intercept), and Ocean Basin in which the catch takes place, which was included as a random effect. Due to a heavily skewed distribution of total mortality estimates across countries, we used log(total mortality) as the response variable in the model. We fit the model using the brms package in R. We ran seven chains with 4000 iterations each and a warmup period of 1000 iterations. We increased the adapt delta control variable to 0.99 and the maximum tree depth to 25 to improve model convergence. We assessed convergence based on visual inspection of trace plots and ensured that Gelman Rubin diagnostics (R-hat values) were <1.01 for all parameters. Regions with the highest mortality rates and weakest regulatory frameworks were flagged for urgent intervention, and existing management approaches were reviewed (SI11, 12).

A detailed description of the methodology used is provided in SI_Doc1.

3. Results

3.1. Domestic protections and international agreements

Globally, 44 countries have enacted domestic legal protections for mobulids. Thirty-five protect all mobulids found in their EEZ, either through (i) domestic legislation pertaining to mobulids ($n = 28$) or (ii) through shark and ray sanctuaries ($n = 7$), and nine protect some species (Fig. 2).

Of the 55 countries without domestic protections, whose fishers catch mobulids, 44 are Party to international convention(s) with *Decisions* or *Resolutions* to fully protect mobulids (described in SI10). These conventions include (i) the Barcelona and/or Bern Conventions, which protect the spinetail devil ray *Mobula mobular* ($n = 11$); (ii) the Cartagena Convention, which protects the oceanic manta ray *Mobula birostris* ($n = 6$); and (iii) CMS, which protects all mobulids and their habitats ($n = 44$) (Fig. 2). Additionally, eight countries that are not Party to these conventions are members of one or more tRFMOs (i.e. ICCAT, IOTC, WCPFC, IATTC), all of which have adopted policies to prohibit landing and trading mobulids for certain fishing gears (Fig. 2). Only three range states without domestic mobulid protections (Myanmar, Palestine, and Qatar) are part of neither tRFMOs nor conventions.

The first mobulid-specific legislation was enacted by New Zealand in 1953, followed by Greece in 1981. The number of domestic protections enacted annually increased significantly after (1) the adoption of the first listing on CMS in 2011 (mean trend before adoption = 0.2 policies/year, mean trend after = 2.5), and (2) the first listing on CITES in 2013 (mean trend before = 0.3, mean trend after = 2.25) (Fig. 3).

3.2. Trends in global mobulid fisheries

3.2.1. Official mobulid catch

Eleven countries (Colombia, Ecuador, Indonesia, Kenya, Liberia, Mauritania, Mexico, Pakistan, Peru, Puerto Rico, and Sri Lanka) reported catching mobulids under three categories to the FAO between 1998 and 2023: 'Giant manta', 'Mantas, devil rays NEI' ('nei' refers to 'not elsewhere included'), and 'Mantas, devil rays, etc. NEI' (FAO, 2024; SI5). Between 1998 and 2016, combined total reported catches increased from 342 to 8083 t. These catches then declined by 87 % until 2023 (1028 t) despite an increase in the number of countries reporting from 2016 onwards.

Among publicly available tRFMO data, nine countries reported mobulid catches to ICCAT under Task 1 data (Canada, Curaçao, El Salvador, Spain, France, Guatemala, Guinea, Panama and Venezuela), while four countries reported catches under Task 2 (Brazil, Canada, France, and Venezuela) (SI6). Guinea reported zero catch. Brazil, Canada, and Venezuela reported catching only *M. birostris*. In contrast, other countries reported catching up to four mobulid species (i.e., *M. birostris*, *M. mobular*, *M. thurstoni*, and *M. tarapacana*), with catches for all four species reported only by France (SI6). Four countries reported mobulid catches to the IOTC (Kenya, Pakistan, Sri Lanka, and Tanzania), and all except Tanzania declared these catches as originating from artisanal fisheries. Kenya and Tanzania reported catching only *M. mobular*, while Pakistan reported catching *M. mobular* and other unidentified mobulids. Sri Lanka reported catching 'mobulids' without species-specific information (SI6). The mean yearly reported mobulid catch was highest for Pakistan (73,909 t, 1987–2023), followed by Sri Lanka (20,000 t, 2019) and Tanzania (17,000 t, 2022).

3.2.2. Global mobulid catch estimates and declines

Based on data collected for SV and LV fisheries across 87 countries and two tRFMOs, an estimated total of 264,520 (95 %CI: 184,407–344,987) individual mobulids are caught globally each year (SI9). Mobulid catch in SV fisheries constitutes 85 % of the global catch and 87 % of the global mortality. Mobulids were either targeted, or caught as incidental catch (retained or discarded) in at least 92 of the 99 countries for which data were available (SI9). Experts were not aware of mobulid catch within, or by, the remaining seven countries (Cambodia,

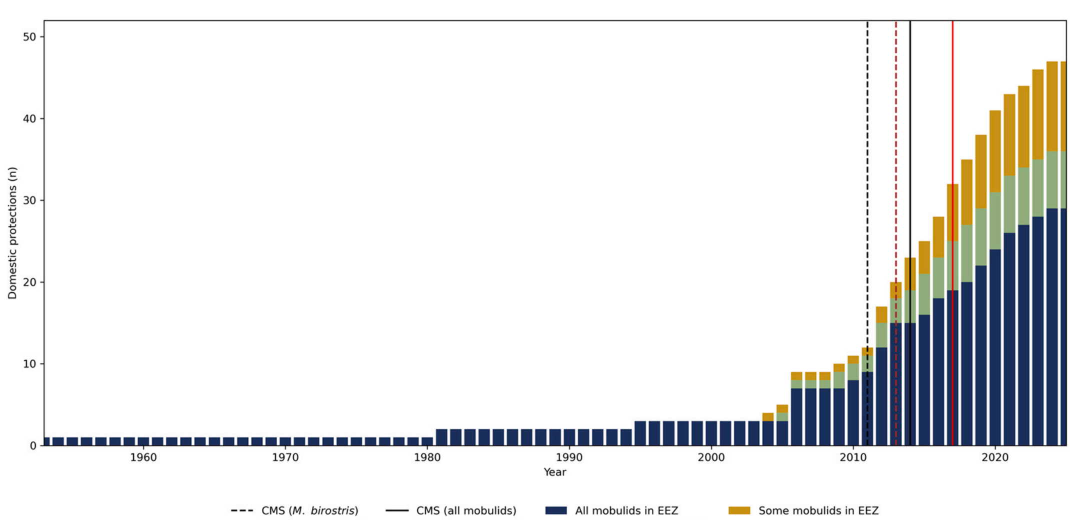

Fig. 3. Cumulative number of domestic protections covering mobulids globally by year they came into force. Both active and superseded laws are shown for six countries where national protections were extended to additional species (SI4).

Comoros, Israel, Kuwait, Montenegro, Singapore, and the United Kingdom).

Among countries that catch mobulids, landing and/or catch declines ranging between 51 and 99 % were recorded in eight (SI7). In Mozambique, sightings per unit effort (SPUE) of multiple species declined by 81–99 % over 21 years (standardised decline: ~3.9–4.7 %/year) (Venables et al., 2025). Similarly, in Costa Rica, SPUE for *M. birostris* declined by 89 % (~4.2 %/year) and *Mobula* spp. by 78 % (~3.7 %/year) over 21 years (White et al., 2015) (SI7). An 80 % decline in SPUE was also observed for *M. birostris* in the Philippines over 16 years (~5 %/year) (Rambahiniarison et al., 2023), and in the USA for *M. tarapacana*, by 47 % over 11 years (~4.3 %/year) (Ward-Paige et al., 2013) (SI7).

Declines were also reported for LV tuna fisheries in the Eastern Pacific Ocean (multiple species, 51–99 % overall, 2.7–19.7 %/year) (SI7). In the coastal trawl survey conducted in the southeastern USA, operating between Cape Hatteras, North Carolina, and Cape Canaveral, Florida, CPUE of *M. hypostoma* declined by 83 % (~4 %/year) over 20 years (2002−2022) (SEAMAP, 2022; Boggio-Pasqua et al., 2025 [In review]) (SI7). Overall, the largest mean declines for all mobulids by country occurred in the Indian Ocean, specifically in Pakistan (95 %; ~12–16.4 %/year) (Moazzam, 2018; IOTC, 2024) and Mozambique (93 %) (Venables et al., 2025). However, the most rapid declines were for all mobulids off Mexico (24.8 %/year, over four years), Kenya (16.8 %/year, over five years), and off Pakistan (mean 15.1 %/year over 6–8 years) (Moazzam, 2018; IOTC, 2024; FAO, 2024; SI7).

Declines in landings were suspected by experts in 18 countries (i.e., Bangladesh, Benin, Cameroon, Côte d'Ivoire, Ecuador, Gabon, Ghana, Guinea, Honduras, India, Indonesia, Madagascar, Mexico, Mozambique, Peru, Republic of the Congo, South Africa, and Sri Lanka). However, in

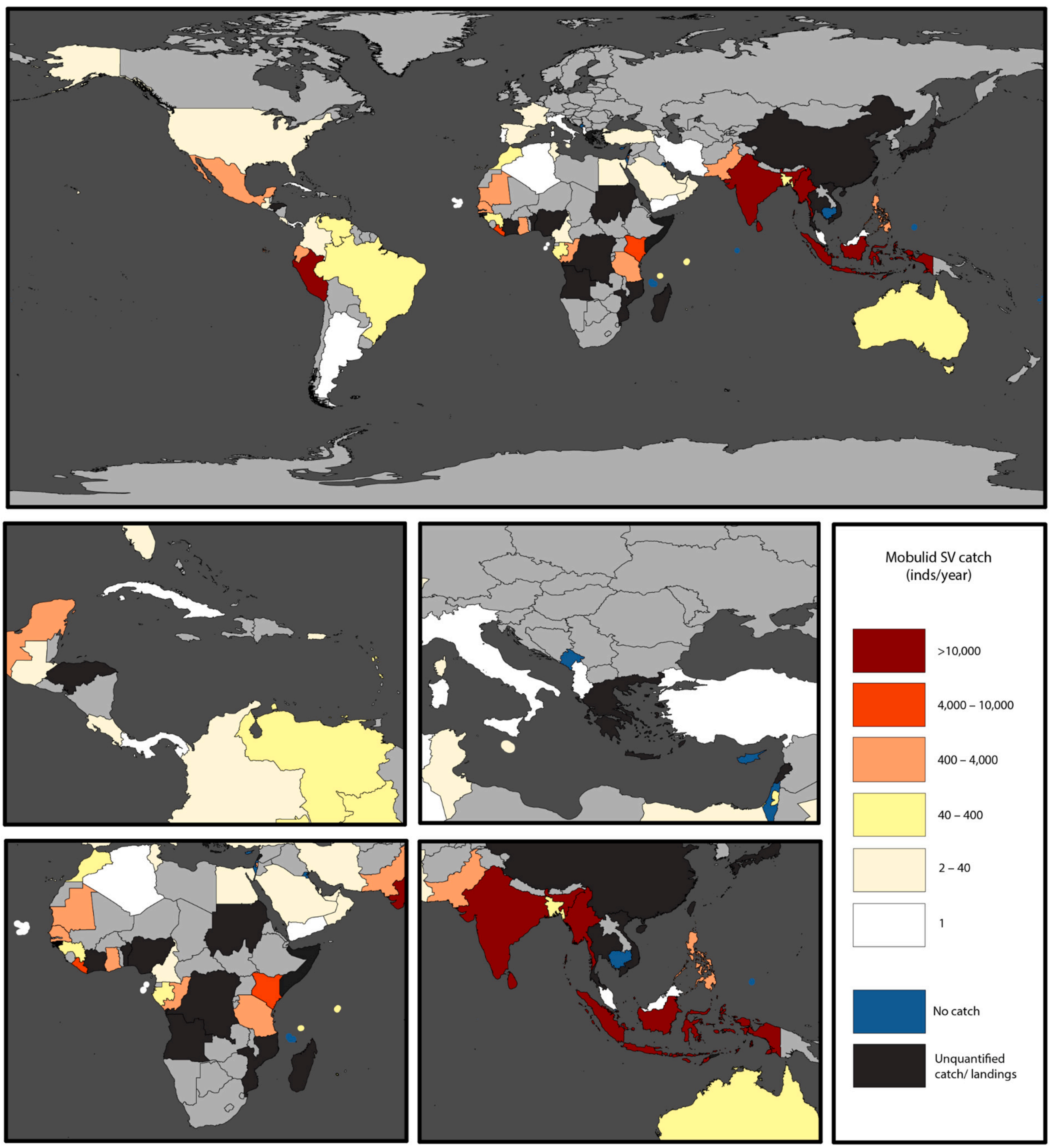

Fig. 4. Global estimated mobulid catch by small vessels (<15 m).

11 of these 18 countries, long-term landings data were unavailable to confirm the scope and magnitude of declines. Among quantified declines, the standardised decline rate was positively correlated with the year of first observation (Poisson GLM, df = 36, $p < 0.001$***, z-value = 8.1).

3.3. Small vessel (< 15 m) fisheries

3.3.1. Key countries and fishery characteristics

Globally, 76 countries catch mobulids in SV fisheries (SI2). Of these, catch could not be quantified in 25 countries due to a lack of fisheries data. Moreover, nine countries systematically discard any mobulids caught, with post-release mortality estimates unavailable (Cyprus, France, Italy, Japan, Maldives, Portugal, Spain, Thailand, the USA, and Palau). Across 47 countries for which data were available, an estimated 225,047 (95 % CI: 157,016–293,260) mobulids were caught in SV fisheries annually, and an estimated 224,958 (95 % CI: 156,959–293,134) mobulids were landed. Twenty-eight countries are known to occasionally discard mobulids in favour of other more valuable target species, which could not be accounted for here.

Five countries caught an estimated >10,000 mobulids per year: Indonesia (27.0 %, n = 60,760 ± 45,588), India (23.4 %, n = 52,570 ± 19,707), Sri Lanka (23.0 %, n = 51,701 ± 38,340), Myanmar (12.0 %, n = 27,000*, expert estimate), and Peru (5.1 %, n = 11,520 ± 4123) (Fig. 4). Two countries caught between 4000 and 10,000 mobulids per year: Kenya (2.3 %, n = 5190) and Liberia (1.9 %, n = 4171 ± 4346). Nine countries caught between 400 and 4000 mobulids per year: Mexico (1.1 %, n = 2459), Philippines (1.0 %, n = 2219), Senegal (1.0 %, n = 2183 ± 1104), Pakistan (0.6 %, n = 1313 ± 644), Ecuador (0.4 %, n = 986 ± 362), Ghana (0.3 %, n = 683), Tanzania (0.2 %, n = 520), Mauritania (0.2 %, n = 461 ± 602), and Republic of the Congo (0.2 %, n = 431) (Fig. 4). Jointly, these countries accounted for 99.6 % of global SV mobulid catch (SI2). Seven countries caught an estimated 40–400 mobulids per year (Guinea, Bangladesh, Venezuela, Brazil, Palestine, Morocco, and Australia). Additionally, 16 countries caught an estimated 2–40 mobulids per year, while estimated catch was only one mobulid per year in 11 countries (Fig. 4, SI2).

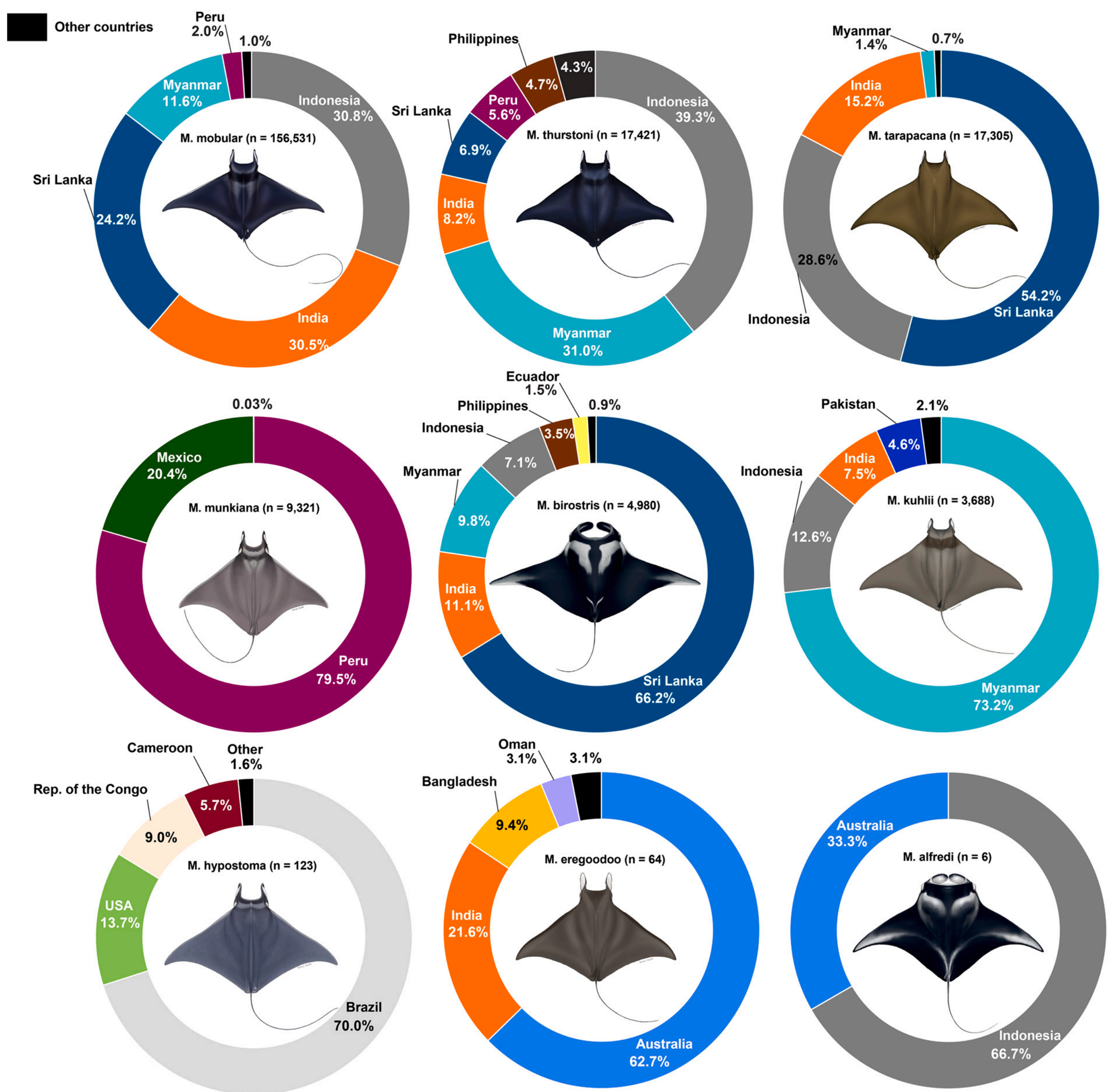

Fig. 5. Primary countries contributing to mobulid SV species-specific catch. Percentages indicate their contribution to global catch. Other (black): combined contribution of additional countries. N = species-specific number of mobulids recorded, where available. Mobulid illustrations: © Marc Dando.

3.3.2. Species-specific SV catch

Species-specific catch data for mobulids in SV fisheries, where available, suggests that *M. mobular* dominates the catch globally (74.7 %), followed by *M. thurstoni* (8.3 %), *M. tarapacana* (8.3 %), *M. munkiana* (4.5 %), *M. birostris* (2.4 %), *M. kuhlii* (1.8 %), *M. hypostoma* (0.1 %), *M. alfredi* (<0.1 %), and *M. eregoodoo* (<0.1 %).

Indonesia (30.8 %), India (30.5 %), and Sri Lanka (24.2 %) caught most *M. mobular*, while Indonesia (39.3 %) and Myanmar (31.0 %) caught most *M. thurstoni* (Fig. 5). Sri Lanka caught most *M. tarapacana* (54.2 %) and *M. birostris* (66.2 %), while Peru caught most *M. munkiana* (79.5 %), a species endemic to the Eastern Tropical Pacific (Fig. 5). For the two pygmy devil ray species endemic to the Indo-West Pacific, Myanmar was estimated to have caught most *M. kuhlii* (73.2 %), while Australia took most *M. eregoodoo* (62.7 %, albeit in now defunct bather-protection nets off New South Wales) (Fig. 5). Catch of the Atlantic endemic *M. hypostoma* was dominated by Brazil (70.0 %) (Fig. 5).

3.3.3. Gear types in SV fisheries

Drift gillnets were reported as the main gear responsible for mobulid captures in SV fisheries (Fig. 6, SI2). This gear type dominated the catch in 26 countries, including the five top mobulid fishing nations. Yet, the relative contribution of other gear types to overall mobulid catch varied across species and locations. For example in Peru, 47 % of *M. munkiana* landings occurred in drift gillnets and 44 % occurred in purse seines, while 87 % of *M. mobular* and 80 % of *M. thurstoni* were landed by drift gillnets (Rojas-Perea et al., 2025).

Following drift gillnets, the largest catches were in set gillnets ($n = 8$ countries) followed by longlines ($n = 4$), trawl nets ($n = 2$), purse seines ($n = 2$), and tuna traps ($n = 1$) (Fig. 6). In 33 countries, the main gear responsible for mobulid catch was unknown. Selective gears, including harpoons, were occasionally used to catch mobulids in 13 countries (SI2).

3.4. Large vessel (>15 m) fisheries

3.4.1. Key countries and ocean regions

We estimated LV catch and mortality using catch records from 37 flag states, and two tRFMOS (the IATTC and the WCPFC) combined with published AVM rates. Globally, catch was estimated at 39,473 (95 % CI: 27,315–51,801) mobulids per year in LV fisheries, resulting in mortality of 34,390 (95 % CI: 23,561–42,256) mobulids annually (SI3).

Countries were grouped according to the magnitude of their reported LV catch. The largest reported LV mobulid catches (>5000 mobulids per year) were from India (51.8 %, $n = 20{,}444 \pm 7664$) and WCPFC fisheries not identified by flag state (16.9 %, $n = 6664 \pm 10{,}326$) (Figs. 7, 8a). Between 500 and 5000 mobulids per year were taken in IATTC fisheries not identified by flag state (6.7 %, $n = 6664 \pm 1509$) and five countries: Spain (6.8 %, $n = 2691$), Liberia (5.2 %, $n = 2055 \pm 2140$), Indonesia (3.1 %, $n = 1240 \pm 930$), Netherlands (1.6 %, $n = 621 \pm 601$), and Sri Lanka (1.3 %, $n = 522 \pm 387$) (Figs. 7, 8a). Eight countries caught between 100–500 mobulids per year: Pakistan (1.2 %, $n = 481 \pm 248$), Portugal (1.0 %, $n = 391$), New Zealand (0.8 %, $n = 310$), Brazil (0.6 %, 235), France (0.6 %, $n = 222 \pm 196$), USA (0.4 %, $n = 159$), Japan (0.4 %, $n = 144$), Palau (0.3 %, $n = 100$) (Fig. 7). Eleven countries caught between 20–100 mobulids per year, and ten caught less than 20 (Fig. 7). When comparing mobulid mortality across reporting bodies, estimates varied based on the number of discards and whether they were reported to be alive or not at release, which also varied across gear types (Fig. 8, SI3). We also note that species-specific catch was deemed unreliable across many LV fleets, so LV catch and mortality was only considered at the genus-level (SI3, 6).

Multiple fleets operate in ABNJ, including some distant water fishing nations (DWFNs). Four DWFNs reported mobulid catches in the Indian Ocean (Portugal, Russia, Taiwan (ROC), and the Republic of Korea). Spain, France, and Japan catch mobulids in both the Atlantic and Indian Oceans; the Netherlands and Palau catch mobulids in the Atlantic (Fig. 7, SI3). DWFNs also fish in foreign EEZs, under bilateral or multilateral fishing agreements. For example, Spain and France catch mobulids while fishing for tropical tunas in the EEZ of various west African countries between Guinea and Angola, and in the Mozambique Channel (Clavareau et al., 2020; Johnson et al., 2021; Keijzer et al., 2024); Japan fishes mobulids in the EEZ of Uruguay (Mas et al., 2015); and Dutch trawlers in the EEZ of Mauritania (Zeeberg et al., 2006) (Fig. 7, SI3).

3.4.2. Fishing gear and discards

In LV fisheries, mobulid catch varied significantly across gear types (Figs. 8b, 9). However, gear type was unknown for 60 % of the catch (for India, Liberia, and Indonesia). Purse seines took most LV mobulid catch (18.6 %), followed by longlines (12.0 %), drift gillnets (7.7 %), and trawlers (1.6 %) (Fig. 9). Purse seines were also the leading cause of mortality in LV fisheries (19.7 %), followed by drift gillnets (5.6 %),

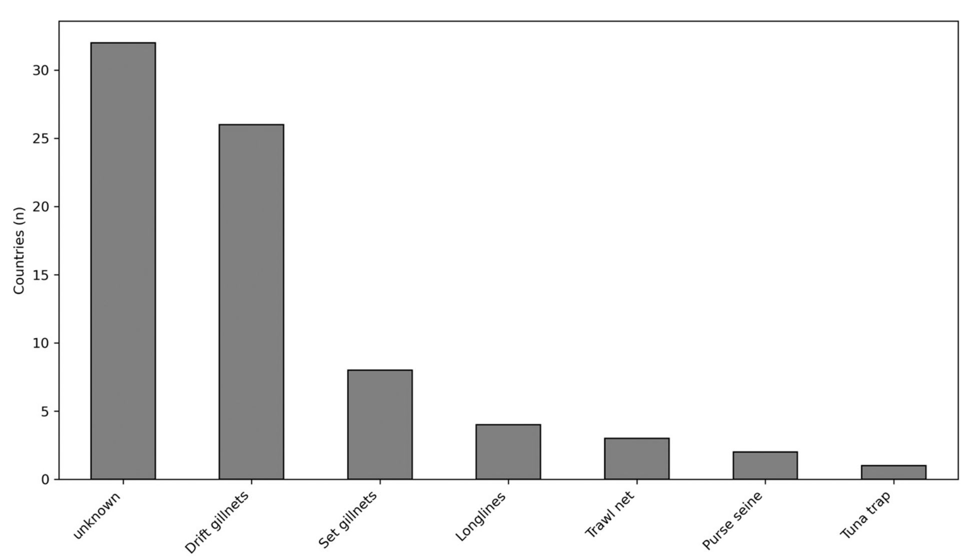

Fig. 6. Main fishing gear type in which mobulids are reportedly caught across SV fisheries globally. Number of countries (n) where mobulid catch is predominantly by stated gear.

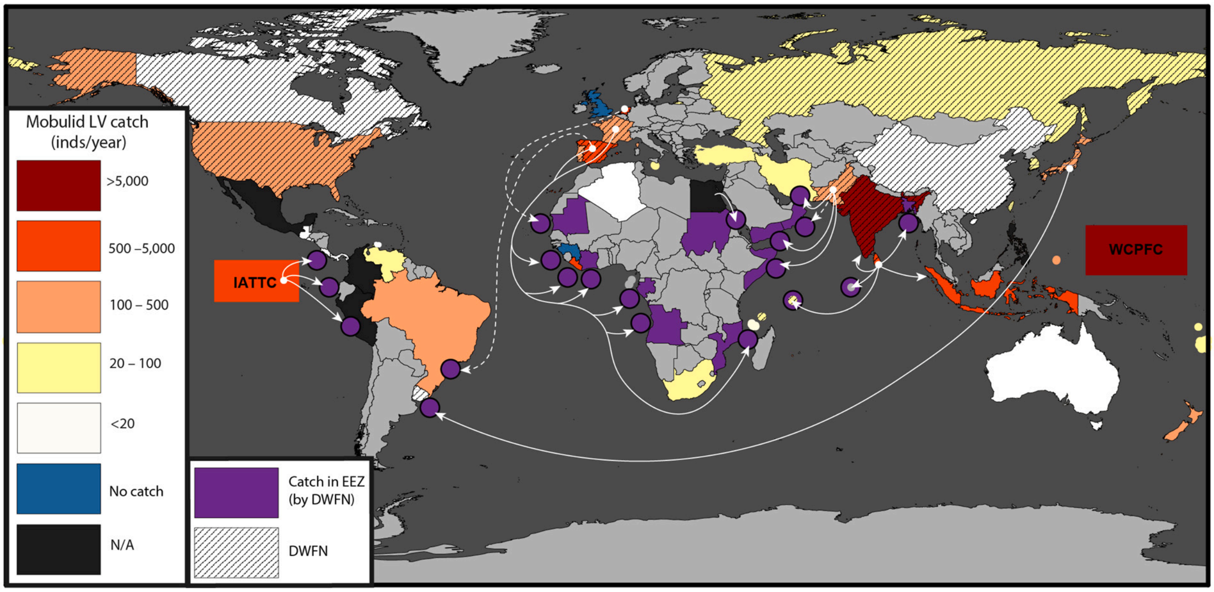

Fig. 7. Global large vessel (>15 m) mobulid catch. Mobulid catch estimates per year, for flag states and two tRFMOs (IATTC and WCPFC). Catch by DWFNs (diagonal stripes) in foreign EEZ is indicated in purple and/or a purple dot. Full white lines indicate which DWFNs fish in foreign EEZs, while dashed lines indicate fleets no longer operating (i.e., Spanish monkfish gillnet fisheries off Brazil and Dutch trawlers off Mauritania). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

longlines (5.1 %) and trawls (0.6 %), while around 70 % of mortality came from unknown gear (Fig. 9).

Mobulid retention rates were highest in trawlers (54.5 ± 64.3 %) and drift gillnets (51.8 ± 50.1 %) (Fig. 10a). In contrast, retention was much lower in longlines (19.1 ± 37.5 %), and purse seines (21.1 ± 39.3 %), despite important variations across fleets for all gear types (Fig. 10a). For example, Brazil and Venezuela retained 100 % of mobulid longline catch, while Fiji retained 89 %, and WCPFC longline fisheries retained 36 %. All other longline fleets ($n = 19$) had minimal retention rates (0–2 %). Three countries (Algeria, Iran, and Türkiye) retained 100 % of mobulids incidentally caught in purse seines, while El Salvador retained 48 % (in the Atlantic), but all other purse seine fleets ($n = 13$), including in the IATTC and WCPFC Areas, retained very little (0–3.2 %).

Purse seines and gillnets had the highest average AVM rate, with 57.3 ± 36.9 % and 50.0 % of mobulids discarded dead (Fig. 10b). The Dutch trawler fleet that previously operated off Mauritania discarded 25 % of mobulids dead, while employing a filter-grid and an escape tunnel; this AVM rate may not reflect that of other trawl fleets (Fig. 10b, Zeeberg et al., 2006). Longlines had the lowest AVM rate (6.7 ± 8.1 %) (Fig. 10b).

3.5. *Estimates of mobulid mortality across regions and fisheries' contexts*

Globally, mobulid fisheries mortality (the sum of reported SV landings and LV retention and AVM, but excluding delayed discard mortality) was estimated at 259,349 (180,693–338,217) individuals per year (SI11). Five countries are responsible for 87 % of identified global mobulid mortality, mostly attributed to SV fisheries: India (28.2 %, $n = 73{,}014$ inds/year), Indonesia (23.9 %, 62,000 inds/year), Sri Lanka (20.1 %, 52,223 inds/year), Myanmar (10.4 %, 27,000), and Peru (4.4 %, 11,520) (Fig. 11). Confirmed landing declines were recorded in all the above except Myanmar, which has no long-term fisheries monitoring. Over 97.5 % of mobulid mortality is attributed to these and twelve additional countries (Liberia, Kenya, Mexico, Philippines, Senegal, Pakistan, Spain, Ecuador, Ghana, Tanzania, Mauritania, and Republic of the Congo) (Fig. 11). Declining population trends were reported across countries with varying mobulid catch and mortality rates. Moreover, multiple unquantified landings declines were perceived by experts in countries lacking trend data (i.e., off west Africa, Madagascar, and Honduras) (Fig. 11). Experts also indicated that mobulids are incidentally caught by Egyptian trawlers in seasonal IUU fishing operations in Sudanese waters.

Comparing mobulid catch and mortality across ocean basins shows that the Indian Ocean dominates both reported global catches (72 %, $n = 191{,}528$) and estimated global mortality (74 %, n = 191,010), followed by the Western and Central Pacific Ocean (WCPO), accounting for 15 % of global catch ($n = 40{,}603$) and mortality ($n = 38{,}134$) (Table 1). Notably, SV fisheries were responsible for most mortality in the Indian Ocean (88 %), and WCPO (80 %) (Table 1). The Eastern Pacific Ocean comprised 7 % of global catch ($n = 17{,}663$) and mortality (n = 17,650), while the Atlantic Ocean comprised 5 % of global catch ($n = 14{,}425$), and mortality ($n = 12{,}341$) (Table 1). LV fisheries accounted for 42 % of the estimated catch in the Atlantic Ocean, but this is likely an artefact of high observer coverage in ICCAT and generally low monitoring of SV fisheries, especially off West and Central Africa. Finally, the Mediterranean Sea had a relatively smaller contribution to global catch and mortality (<1 %), though we identified highly localised mortality hotspots (Table 1).

There were also notable differences in total mobulid mortality across fishery types (Fig. 12). The majority of mobulid mortality resulted from retained incidental catch and/or targeted catch (72 %, $n = 186{,}712$ individuals) across 21 countries (Fig. 12a). Retained and discarded incidental catch and/or targeted catch represented 22 % ($n = 57{,}502$) of mortality across six countries (Fig. 12a). Retained and discarded incidental catch accounted for only 4 % ($n = 10{,}238$) of mobulid fisheries mortality (in 32 countries), with a similarly low contribution (5 %) to global catch (Fig. 12a). Finally, discarded incidental catch accounted for 0.1 % ($n = 251$) of global mobulid mortality, resulting from interaction with gear in LV fisheries across 11 countries, although post-release mortality was not accounted for here (Fig. 12a). The relative contribution of SV fisheries to mobulid mortality also greatly differed across fishery types, with increasing SV proportions for fisheries with greater retention, and targeted fisheries (Fig. 12b).

Mobulid mortality varied substantially across policy context and trade categories (Fig. 13a and b). Over half of mobulid mortality (55 %, $n = 140{,}241$) was by fisheries in countries protecting only some mobulids within their EEZ, and an additional 26 % ($n = 66{,}285$) was by countries that haven't implemented international agreements to protect

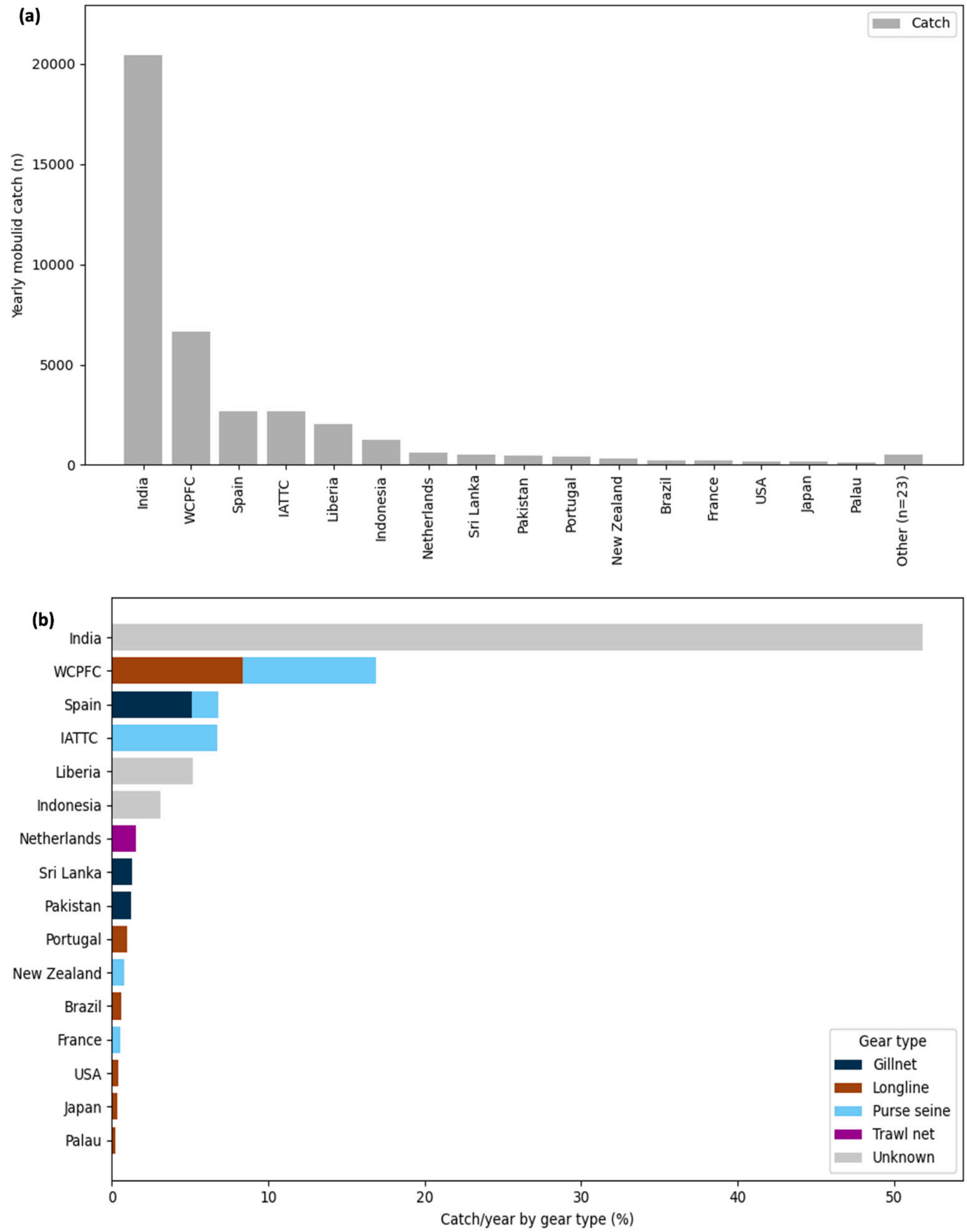

Fig. 8. (a) Mobulid catch/year (grey bars), in LV fisheries for flag states, the IATTC, and the WCPFC; (b) percentage of mobulid catch/year in LV fisheries for the top 14 flag states and two tRFMOs, by gear type.

mobulids (CMS, Barcelona, Bern and Cartagena Conventions). Notably, areas with no protective policies accounted for 11 % (n = 27,091), whereas mortality was lowest in EEZs with full mobulid protection (8 %, n = 20,980) and negligible in regions with shark and ray sanctuaries or tRFMO-only measures (Fig. 13a).

From a trade perspective, demand for mobulid products clearly influenced mobulid fisheries mortality (Fig. 13b). The majority of mortality (68 %, n = 164,327 per year) occurred in six countries, where both domestic meat consumption and international export of meat and gill plates occurs. Furthermore, 22 % of mortality (54,442 individuals) occurred in five countries where meat is consumed domestically and gills are traded internationally, but there is no international meat trade (Fig. 13b). Mortality of mobulids taken exclusively for domestic consumption was widespread across 31 countries and relatively high (23,374 individuals), however, fisheries mortality in 16 fishing nations where mobulids are neither consumed nor traded was low (4327 individuals) (Fig. 13b). Mortality resulting from domestic consumption and international meat trade only, without any known gill plate trade, was a less common scenario, occurring in only four countries, and also low (1460 individuals) (Fig. 13b).

Our analysis of the drivers of total mortality in mobulid fishing nations revealed that countries using primarily drift gillnets had higher mobulid mortality rates than almost all other gear types, however this gear type was used predominantly in lower Human Development Index (HDI) countries (Fig. 14 in SI_Doc1). The additional effects of HDI on mobulid mortality were significant (Fig. 14). Gill plate export was also associated with significantly higher mobulid mortality; while protection status and ocean region were not (Fig. 14).

4. Discussion

We provide a first global overview of fisheries-related threats and

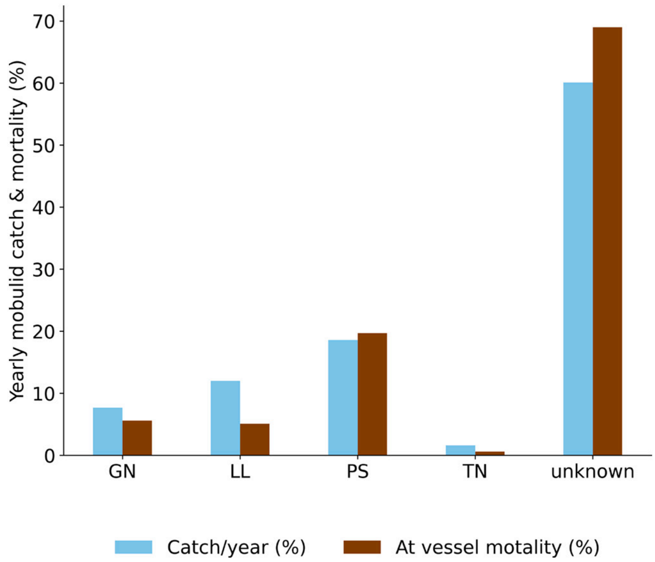

Fig. 9. Proportion of annual mobulid catch (blue) and mortality (brown), across different gear types. GN: gillnet, LL: longline, PS: purse seine, TN: trawl net. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

estimate of mobulid mortality in fisheries to identify priority policy actions. We estimate that over 264,000 mobulids are caught in fisheries each year. Although population size and trends data are generally lacking for mobulids, decreasing sightings per unit effort and reported catch and landings suggest these global catches are substantial, and have contributed to overfished populations in many parts of the world (Lewis et al., 2015; Moazzam, 2018; Fernando and Stewart, 2021; Venables et al., 2025; Laglbauer et al., 2025). We reveal that (1) SV gillnet fisheries pose the greatest threat to mobulid populations, (2) mobulid population declines are intensifying due to combined effects of SV and LV fisheries, and (3) targeting and retention of mobulids is largely demand-driven. Further, we argue that (4) reduction of mortality requires area-based management, effort limitation (e.g., gillnet restrictions), and live-release, and (5) there is an urgent need to improve the enforcement of CMS, CITES, and tRFMO measures, through national-level policies. We propose urgent actions and identify priority locations to address the greatest global threat to mobulids: overfishing and its underlying drivers (Croll et al., 2016; Stewart et al., 2018).

4.1. *SV gillnet fisheries are the highest threat to mobulids*

The majority of reported mobulid fishery-induced mortality (87 %) originates from SV fisheries and is highly concentrated across five countries (India, Indonesia, Sri Lanka, Myanmar, and Peru), which jointly account for 85 % of the estimated global catch and 87 % of global mortality. These countries overlap with areas of highest species diversity for mobulids, and the widespread use of non-selective fishing gear leads to high catches (Raje and Zacharia, 2009; Fernando and Stewart, 2021).

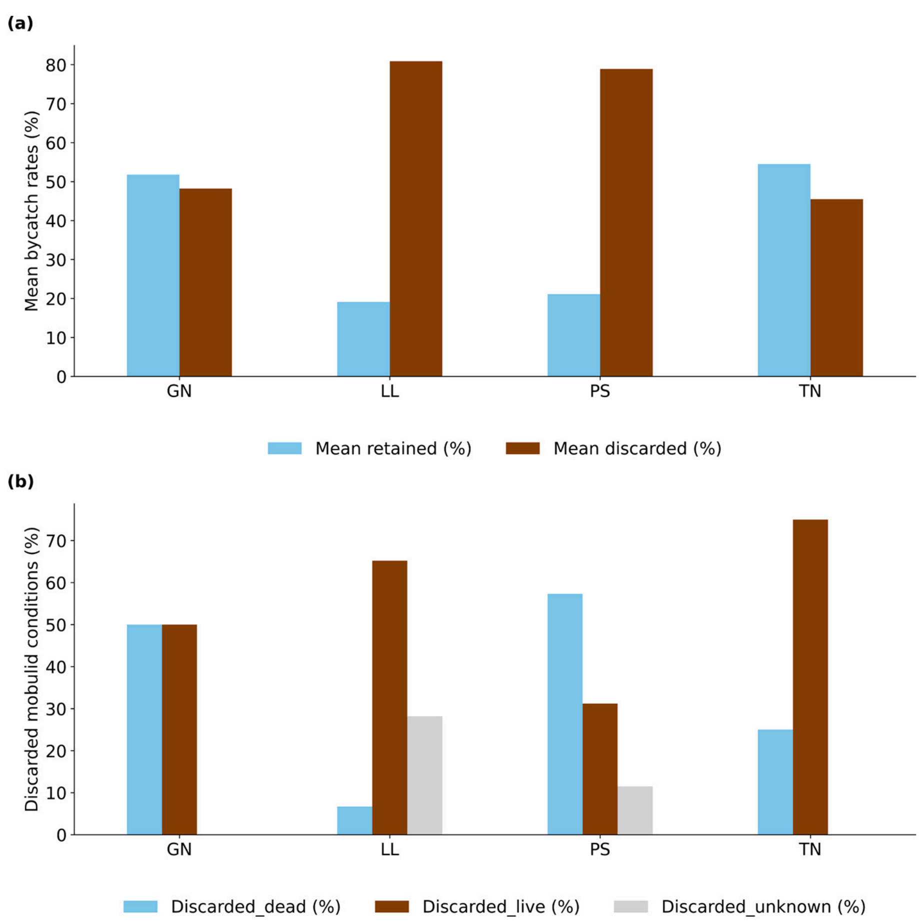

Fig. 10. (a) Incidental catch rates: mean percent (n) of mobulids retained (blue) and discarded (brown), and (b) at-vessel condition of discarded mobulids: mean percent (n) of mobulids discarded dead (blue), discarded live (brown), and discarded in an unknown condition (grey), across different gear types. GN: gillnet, LL: longline, PS: purse seine, TN: trawl net. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

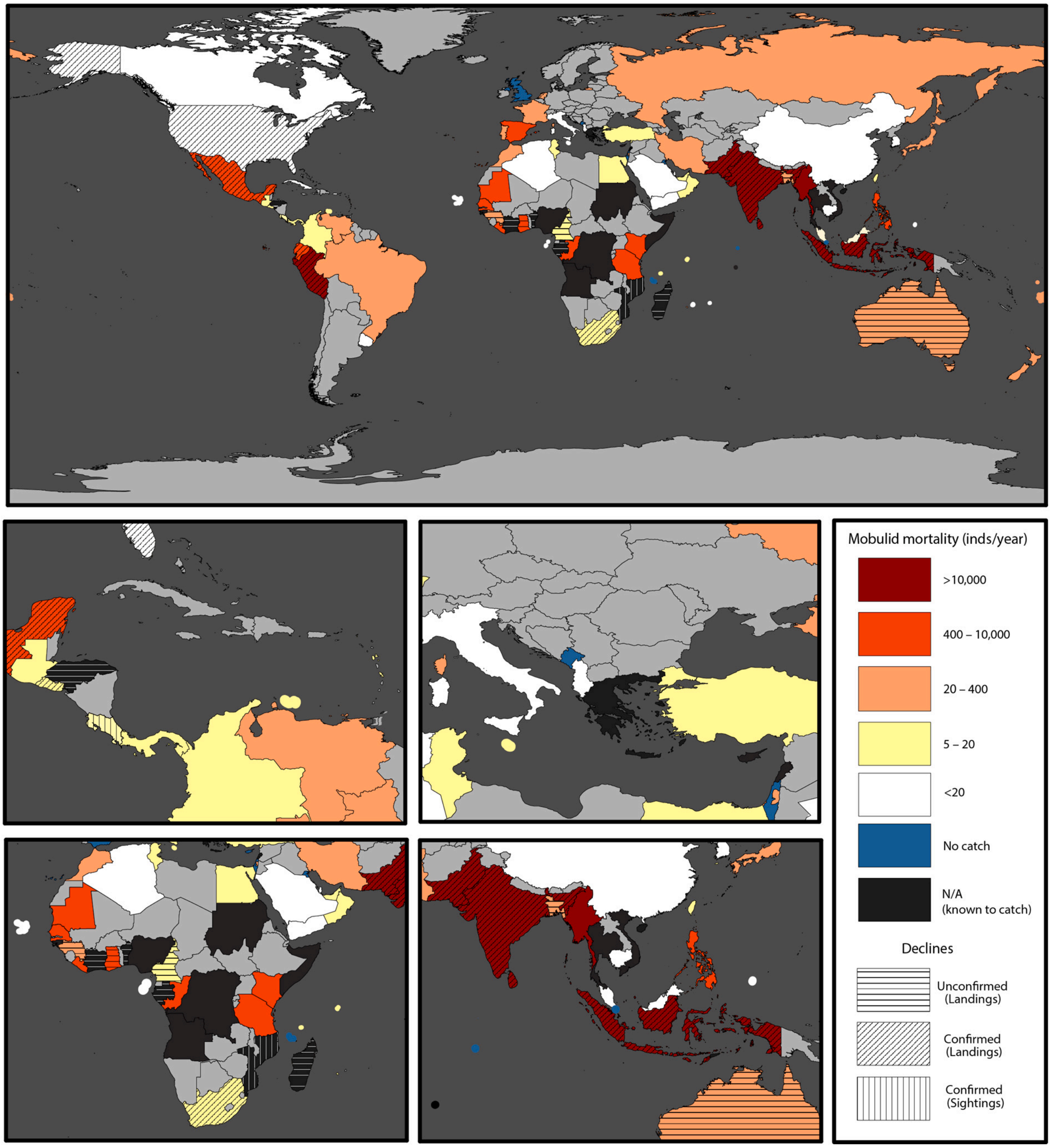

Fig. 11. Combined estimated mobulid fisheries mortality across SV and LV fisheries. Countries are classified based on estimated mortality (combined SV landings and LV retention and AVM), in number of individuals per year. Mobulid declines are highlighted based on (i) unconfirmed declines in landings based on expert interviews (horizontal stripes), (ii) confirmed declines based on catch/ landings data (diagonal stripes), or (iii) confirmed declines based on sightings data (vertical stripes) (SI7).

This is exacerbated in India and Indonesia, where suitable habitats for mobulids are distributed throughout especially large EEZs with intense SV fishing pressure (Putra et al., 2020; Chopra et al., 2025 [In review]), and mirrors the situation for many coastal shark species (Karnad et al., 2020; Worm et al., 2024). Mortality rates in these countries are driven by a combination of high domestic consumption of meat, and the value of gill plates in international trade (Guirkinger et al., 2021; Fernando and Stewart, 2021). In contrast, over half of mobulid catching nations are estimated to take fewer than 100 individuals annually, and one third take ten or fewer.

Our analysis of the drivers of total mortality in mobulid fishing nations indicated that export of gill plates had a significant negative effect on mobulid survival (see 4.3), and that countries using primarily drift gillnets had higher mobulid mortality than almost all other gear types (Fig. 13). We note that, while mobulid catchability differs across gears, the prevalence of mobulids in certain gear types also reflects which fleets overlap the most with mobulid habitat and hence which gear types are most commonly used in a given area, or EEZ (Alfaro-Cordova et al., 2017; Lezama-Ochoa et al., 2019; Martin, 2020). Drift gillnets dominated the catch in SV fisheries because of their widespread use, especially in lower HDI countries, whereas other gear types were associated with higher HDI countries. For example, 86 % of mobulid take in the Gulf of Mannar, India, is from drift gillnets, while in East Java, Indonesia, it reaches 92 % (Mohanraj et al., 2024; Laglbauer et al.,

Table 1
Global mobulid catch and mortality (for SV and LV fisheries) across ocean basins. Yearly catch in number of individuals (n) represents summed totals for SV and LV fisheries, and their relative percent contribution. Yearly mortality represents summed totals for SV landings and LV retention and AVM, and their relative percent contribution. The catch and mortality of DWFNs are accounted for in the ocean basin(s) based on available data. Mortality (vs. catch) represents the proportion of each ocean region's mortality relative to catch.

	Ocean regions					
	Indian	Western & Central Pacific	Eastern Pacific	Atlantic	Mediterranean	Total
Catch (n)	191,528	40,603	17,663	14,425	301	264,520
Global catch (%)	72	15	7	5	<1	100
Mortality (n)	191,010	38,134	17,650	12,341	212	259,348
Global mortality (%)	74	15	7	5	<1	100
SV catch (vs. LV catch) (%)	88	80	85	58	78	NA
SV mortality (vs. LV) (%)	88	81	85	67	84	NA
Mortality (vs. catch) (%)	>99	94	>99	86	71	NA

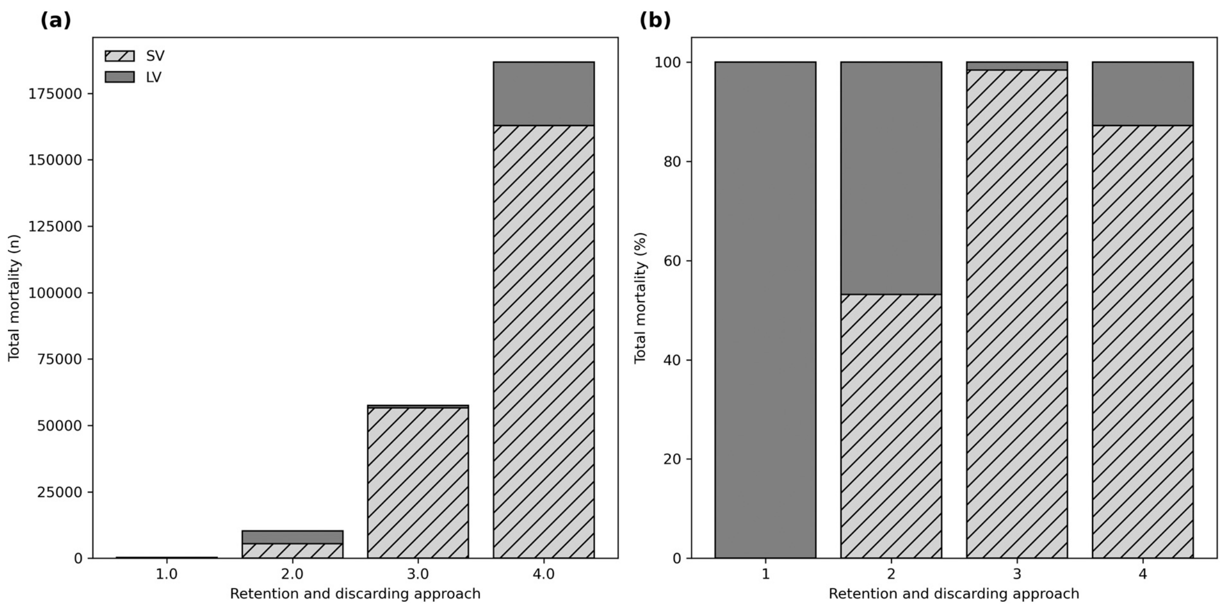

Fig. 12. Combined mortality in SV and LV fisheries (a: in numbers; b: in percentages) by retention and discarding approaches, where, 1: Discarded incidental catch, 2: Retained and discarded incidental catch, 3: Retained and discarded incidental catch and/or targeted catch, 4: Retained incidental catch and/or targeted catch.

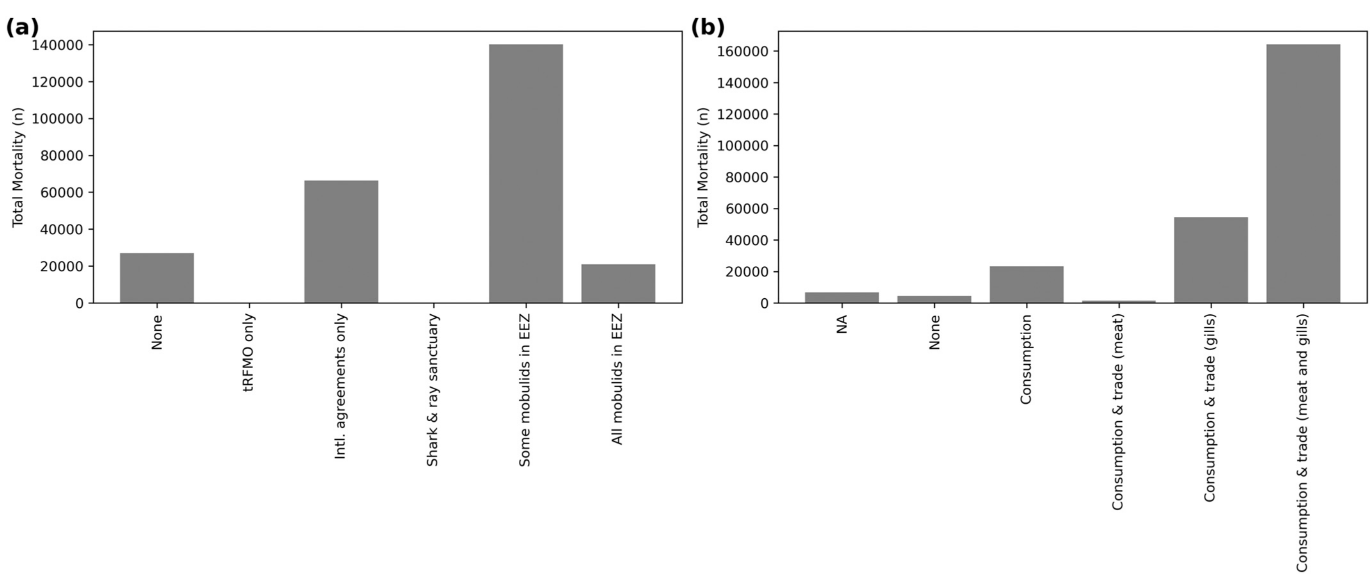

Fig. 13. Total mobulid mortality by (a) protection category (None, tRFMO only, international agreements only, shark & ray sanctuary, some mobulids in EEZ, and all mobulids in EEZ); and (b) trade category: NA (trade status unknown), none (no trade in meat or gill plates), consumption (domestic meat trade), consumption & trade (meat), consumption & trade (gills), and consumption & trade (meat and gills).

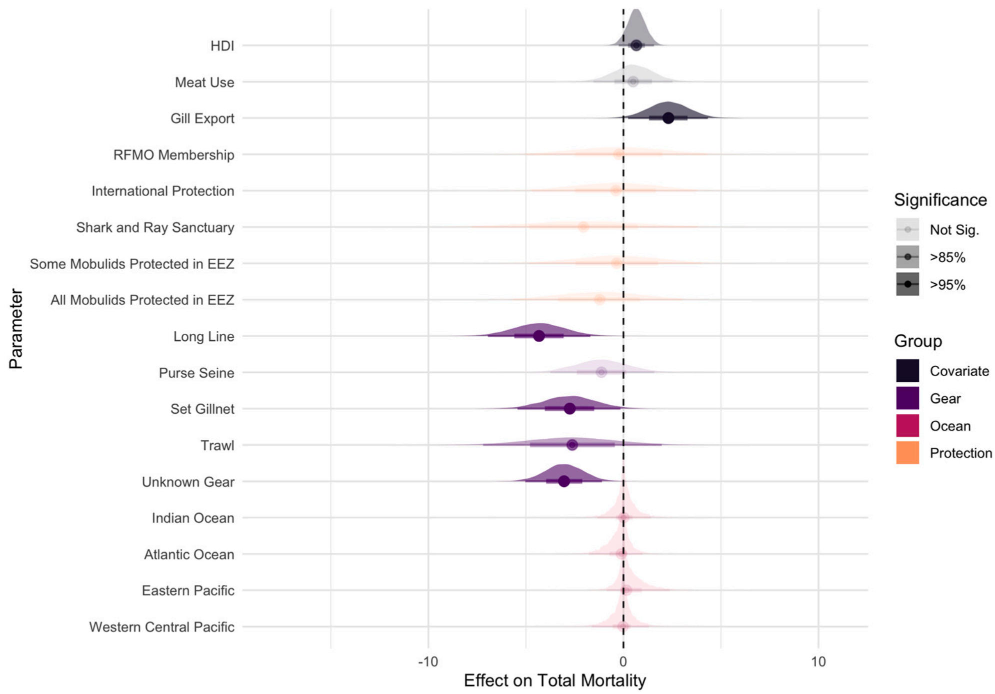

Fig. 14. Posterior estimates for covariate effects on mobulid fisheries mortality (combined SV and LV by country). Estimates are on the log scale as log(mortality) was the response variable. Drift gillnets were modeled as the intercept, so gear type effects are relative to drift gillnets. Densities reflect the posterior distributions of covariate effects, dots are the median, thick horizontal lines are the 66th percentile, and thin horizontal lines are the 95th percentile intervals. Distributions are shaded by their significance, with lightest colors indicating no significant effects, mid shades indicating likely significant effects (>85 % of posterior samples > or <0), and darkest shades indicating significant effects (>95 %). HDI: Human Development Index (0 to 1). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2025). This reinforces other evidence presented here, suggesting that countries fishing predominantly with gillnets in coastal and shelf waters represent the greatest threat to mobulid populations.

The Indian Ocean emerged as the highest priority for conservation action, accounting for close to three quarters of estimated global mobulid mortality, with the majority arising from SV fisheries (88 %). While at least 31 countries take mobulids in the Indian Ocean, catch is largely dominated by the world's four largest mobulid catchers: India, Indonesia, Sri Lanka, and Myanmar. These countries all consume mobulid meat domestically and/or export meat and/or gills to Asian countries (Palacios et al., 2025). Mobulid meat is also widely consumed across the Indian Ocean, along with other elasmobranchs, as a generally cheap protein source unaffected by fisheries management (Jabado and Spaet, 2017; Jabado et al., 2018; Pollom et al., 2024; Palacios et al., 2025). Despite nearly a decade of international agreements (all are Parties to CITES, and all except Indonesia are Parties to CMS) and domestic laws to protect some mobulids in India and Indonesia, declining catch/landing rates (in Indonesia and Sri Lanka), and declining catch trends despite stable or increasing effort (in India) suggest measures are insufficient to recover local populations (Raje and Zacharia, 2009; Lewis et al., 2015; Fernando and Stewart, 2021; Thomas et al., 2022; Laglbauer et al., 2025). In Myanmar, while mobulid catch data are limited, market surveys, interviews with fishers, and trade surveys suggest mobulids likely face similar fishing pressure (Segura-García et al., 2024; Ko Gyi et al., 2025 [In prep.]). Despite the declaration of a national ban on shark fishing, surveys have revealed an active market for mobulid products, with demand for dried mobulid meat sold online, international trade for meat and gill plates, and no restrictions on ray fishing (Howard and Ahmad, 2015). These cases are consistent with our model estimates, suggesting that in some cases national protections have no detectable effect on total mobulid mortality.

4.2. SV and LV fisheries converge on rapidly declining mobulid populations

Declining catch, landing, and sighting trends across mobulids in multiple countries (and the IATTC Area), coupled with expert reports of declines in these and additional countries, strongly suggest that populations are declining globally. Although much of the evidence comes from fisheries-dependent data or expert elicitation, the consistency of observed trends across independent sources (e.g., SPUE, effort-corrected catch rates, and stable or rising effort metrics) (detailed in SI_Doc1) indicates that these declines reflect genuine population trajectories. Importantly, more recent records tend to show steeper reductions, suggesting an accelerating rate of decline, where data is available. Most of the quantified declines were recorded in the Indian Ocean and the Eastern Tropical Pacific. However, large data gaps remain, in particular in the Atlantic Ocean, where estimates suggest only 5 % of the annual mobulid catch occurs. This likely represents an underestimation, due to (1) low data coverage in many parts of the Atlantic despite known mobulid fisheries, especially off west Africa in both SV and LV fleets, and (2) declines reported by experts in seven African countries, which point to potential stock depletions in some areas before regular data collection began, despite relatively lower mobulid catches. We suggest that overfishing, facilitated by policy gaps and inadequate enforcement, is the primary driver of these concerning trends.

Cumulative impacts from LV and SV fisheries on connected mobulid populations can arise across broad spatial scales. For example, highly seasonal and localised catch hotspots for *M. mobular* off Palestine, Morocco, and Türkiye may affect connected populations, since this species undertakes large migrations across the Mediterranean (Akyol et al., 2012; Sakalli, 2017; Abudaya et al., 2018; Kabasakal et al., 2024; El Arraf et al., 2024; Başusta and Özbek, 2017; Notarbartolo-di-Sciara et al., 2025). Furthermore, SV and LV fleets can co-occur, with high mobulid mortality by SV fleets exacerbated by LV fleets catching mobulids inside or nearby local EEZs. For example, in the Eastern Pacific Ocean, Peru, Mexico, and Ecuador were SV mortality hotspots, mostly catching mobulids in gillnets, while prominent LV catch also occurs in the tropical tuna purse seine fishery off Peru and the Costa Rica Thermal Dome, where mobulid declines have occurred (Croll et al., 2016; Lezama-Ochoa et al., 2019; Rojas-Perea et al., 2025). In the Atlantic, for example, DWFN fisheries have fishery agreements and private arrangements to operate in some EEZ waters off West and Central African countries. In this region, experts report declines in mobulid SV landings in countries where DWFN mobulid bycatch is highest (Lezama-Ochoa et al., 2020), particularly in coastal waters off Ghana, Guinea, Mauritania, and the Angolan upwelling system (Lezama-Ochoa et al., 2020). Moreover, Clavareau et al. (2020) identified catch hotspots in the Mozambique Channel, where local mobulid populations are declining severely (Venables et al., 2025). Many developing countries receive an important component of their GDP from selling access rights to their EEZ waters to DWFNs, although benefits to coastal communities who rely on fisheries may be minimal (Gagern and van den Bergh, 2013; Campling et al., 2024). This highlights the importance of considering DWFNs impacts for the conservation of local mobulid populations. Moreover, multiple countries are involved in illegal, unreported, and unregulated (IUU) fishing in foreign EEZs, often as a result of declining national fish stocks (Okafor-Yarwood et al., 2022). For example, in the Indian Ocean, Sri Lankan fishing vessels enter the territorial waters of India, the Maldives, the Chagos Archipelago, and sometimes Indonesia, Seychelles, Madagascar and Bangladesh; Pakistani vessels venture into the EEZ of Somalia, Yemen, Iran, and previously also Oman; and Indian trawlers and gillnetters venture into foreign EEZs (Fernando and Stewart, 2021; Harris and Stevens, 2024).

4.3. Most mobulid fisheries mortality is demand-driven

The majority of mobulid fisheries mortality is driven by demand for domestic meat consumption and international trade of meat and gills. Fisher decisions to target mobulids or retain incidental catch depend upon a wide range of factors, including inter alia vessel and fishing gear capacity, market demand, and fishery regulations (Booth et al., 2019; Rojas-Perea et al., 2025). Drivers of mobulid retention also differ between fleets and locations. In SV fisheries, retention often depends on the relative value of mobulids compared to other species caught, linked to local demand and supply (Guirkinger et al., 2021). For example, in Sri Lanka and Bangladesh, mobulids are taken as target and/or incidental catch, but may be discarded at sea so that more valuable species can be retained (Fernando and Stewart, 2021; Haque et al., 2021). This practice no longer occurs in Bangladesh due to mobulid catch declines, illustrating the complex socio-economic dynamics of retention practices (A. B. Haque, pers. comm.). In LV fisheries, mobulid retention also occurs to a lesser extent, although compliance with tRFMO retention bans is more widespread (Swimmer et al., 2010; Mas et al., 2015; Lezama-Ochoa et al., 2019).

The domestic value of mobulid meat may be higher when demand is specialized, for example for traditional dishes where mobulids are used exclusively or alongside other species, or lower when supplying an indiscriminate, general demand for elasmobranch meat, fishmeal/animal feed, or shark bait (Palacios et al., 2025). For example, in Pakistan mobulids are retained exclusively for fishmeal, leading to one of the lowest mobulid meat values globally (0.35 USD/kg) (Moazzam, 2018; Palacios et al., 2025).

While targeted fisheries are less common than incidental catch globally, they also have the potential to deplete mobulid populations and have caused some rapid local extinctions (Lewis et al., 2015). Harpoons, hooks and other selective gears were historically used to target larger mobulid species (Dewar, 2002; Lewis et al., 2015; Couturier et al., 2012; Croll et al., 2016; Tyabji et al., 2022). These are still used in eastern Indonesia (Booth et al., 2021), by Peruvian communities also targeting billfishes (Rojas-Perea et al., 2025), and in a recently developed directed fishery in Dinagat, Philippines (Acebes et al., 2016). Opportunistic use of harpoons to catch mobulids was also reported across 13 additional countries in this study. The rising value of gills in international trade and a shift to online platforms for trading meat and gills internationally provide greater incentive for targeting mobulids and highlights the relevance of effective domestic protection (Palacios et al., 2025; Ko Gyi et al., 2025 [In prep.]). Moreover, catch in non-selective gear is not necessarily an unintended bycatch of mobulids (Booth et al., 2019); many communities historically targeting mobulids with selective gear shifted to targeting them with non-selective gear as fisheries developed, including off Bohol in the Philippines (Acebes and Tull, 2016), while others transitioned to mixed-species fisheries but still retain mobulids (Booth et al., 2021).

4.4. National management – gaps and priorities

Improved domestic policy frameworks to protect mobulid species and effective compliance mechanisms to reverse population declines are the foundation for curbing mobulid overexploitation in leading fishing and trading nations. We identify Sri Lanka, Indonesia, India, Myanmar, and Peru as highest priority countries for management actions, due to the impact of their fisheries on global mortality rates, documented population declines across Indonesia, India, Sri Lanka, and Peru, and (despite the absence of time series catch data for Myanmar) concern regarding rising domestic demand for mobulid products in Myanmar and its foremost role in the international trade of meat and gill plates (Palacios et al., 2025; Ko Gyi et al., 2025 [In prep.]). We recognise constraints on management capacity in many countries in the Global South, where most mobulid fisheries mortality occurs, aggravated by limited food and economic opportunities in rural coastal areas (Mizrahi et al., 2019; Siddiqi et al., 2024). Hence, appropriate and adaptive frameworks that consider the complexity of local socio-ecological systems should be developed to ensure domestic protections are fairly and efficiently enforced (Dulvy et al., 2017; Karnad et al., 2020).

In Sri Lanka, the world's largest reported gill plate exporter, large-scale fishing operations using small to medium-sized vessels fuel a local and international demand for mobulid meat, amidst landing declines and a complete lack of protection (Fernando and Stewart, 2021; Palacios et al., 2025). India and Indonesia, two of the world's leading elasmobranch fishing nations (Dent and Clarke, 2015; Kizhakudan et al., 2015; Gupta et al., 2022), have protected some mobulid species in their EEZs, but have omitted other species with drastic declines over the past decade, representing a major policy and management gap (Lewis et al., 2015; Laglbauer et al., 2025).

In Indonesia, manta rays (*M. birostris* and *M. alfredi*) have been protected since 2014 and were included in the National Plan of Action (NPOA) for sharks and rays in 2016 (Minister of Marine Affairs and Fisheries, Regulation No. 4/KEPMEN-KP/2014). However, other commonly landed mobulids are not protected, despite evidence of a reduction by 93 % in catch rate for *M. mobular* and up to 99 % landing declines for *M. tarapacana* in Indonesia (Lewis et al., 2015; Laglbauer et al., 2025). Mobulid meat is generally lower in value per kg than that of other fish species or shark meat, however, larger-bodied mobulids can still command whole-body prices comparable to some teleost fishes and other elasmobranchs, depending on market supply (Laglbauer et al., 2025). Mobulid meat is also used in some regional dishes—for example, in East Java.

In India, although all mobulids were included under The Wildlife (Protection) Amendment Act in 2023, only *M. birostris* (Schedule I), *M. alfredi* (Schedule I) and *M. tarapacana* (Schedule II) are granted effective protection due to higher penalties for non-compliance. The other mobulid species are only covered by international trade regulations in Schedule IV. India's NDF for mobulids, produced in 2022 and valid for three years, concluded that international trade in devil ray products does not pose a risk to the survival of Schedule IV species (*M. mobular*, *M. thurstoni*, *M. eregoodoo*, *M. kuhlii*) and that export permits could be granted for products from specimens legally obtained in the IOTC Area (CMFRI Marine Fisheries Policy Series No.21/2022). This is in contradiction of the retention ban in IOTC-managed fisheries, which covers purse seiners, longlines, and gillnets targeting tuna and related species, and only exempts subsistence fisheries taking mobulids for fisher's direct consumption/use (IOTC Resolution 2019/03), and of catch/landings declines (Thomas et al., 2022; Chopra et al., [In review]). Although an estimated 90 % of India's mobulid catch is made by SV fleets, subsistence consumption is rare, with fishers occasionally consuming mobulids while out at sea, since they constitute the lowest value catch (Chopra, pers. comm.). Most mobulid meat is processed and commercialised domestically, especially to meet demand in south-western India, although exports do occur (MRAG, 2012; Karnad & Chopra, pers. comm.). Furthermore, we note that Indonesia and Sri Lanka only consider domestic fisheries operating in ABNJ to fall under tRFMO management, which, under current conditions, precludes any domestic enforcement of tRFMO retention bans. For the same reason, Indonesia does not consider the WCPFC mobulid retention ban to apply to domestic fisheries operating inside its EEZ, despite no stated exemptions (WCPFC, CMM 2019-05).

Karnad et al. (2020) show that listing in Schedule I of India's Wildlife Act has generally not benefitted other elasmobranch populations, except for the whale shark, because sharks are not treated as incidental catch, due to a lack of fisher and trader awareness concerning wildlife conversation policies, among other cultural, biological and economic factors. Indian fishers report increasingly targeting/retaining mobulids due to shark population declines and difficulties with exporting shark fins after the ban on trade (Karnad, pers. comm.). This highlights the need for a combination of fisheries regulations with domestic wildlife protections for mortality reduction to be effective. There are also opportunities to implement management actions in collaboration with the fishing communities that rely on those high-risk fisheries for food security, due to the history and practice of local and informal fisheries co-management bodies in the SV sector, for example in India and Indonesia (Bavinck et al., 2013; Karnad, 2017). Similar approaches will be essential for better protection of mobulids in other priority countries, including in Peru, where fisher pushback has recently arisen in response to protections being extended to all mobulids (Rojas-Perea, pers. comm.).

Other priority nations based on high mobulid mortality hotspots were Liberia, Kenya, Mexico, the Philippines, and Senegal. Among these, Liberia and Senegal require domestic mobulid protection, amidst a general lack of conservation measures for threatened sharks and rays listed in CITES and CMS Appendices (Jabado et al., 2024). Kenya, Mexico and the Philippines require urgent enforcement of existing legislations, especially given rapid mobulid population declines (FAO, 2024; IOTC, 2024; Rambahiniarison et al., 2023). Despite relatively lower mobulid mortality rates, Pakistan, with rapidly declining catches, and Ecuador, with expert-reported declines, should also be prioritized for better enforcement of domestic protections.

Catch hotspots identified here also highlight species-specific policy and management gaps. Despite data limitations, the SV reported catch of each mobulid species was highly concentrated in a few countries. *Mobula mobular* was the most commonly caught species, accounting for three-quarters of SV catch, although *M. thurstoni* dominated the catch in some locations, for example off Bohol, Philippines (Rambahiniarison et al., 2018) and Guinea (Kashey et al., 2025). Notably, *M. thurstoni* also dominated tropical tuna purse seine (LV) catches in the IATTC (Lezama-Ochoa et al., 2019). However, while all other species except *M. tarapacana* have limited habitat ranges, their relatively lower SV catch numbers should be interpreted with caution, since species-specific data are still sparse and misidentifications common (Stewart et al., 2018). For example, while *M. alfredi* is restricted to the Indian and West-Central Pacific Oceans, estimated catch numbers are based on limited data from Indonesia and Australia (in bather-protection nets), while unquantified catches occur, for example, in the Philippines and Mozambique (Acebes et al., 2016; Venables et al., 2025). Moreover, despite relatively lower catch numbers for endemic pygmy mobulid species and isolated populations, such as *M. hypostoma* in the eastern Atlantic, they are intrinsically more vulnerable to fisheries threats and require urgent conservation action (Humble et al., 2025). We conclude that all mobulid species need national protection, even if they do not occur within top-fishing nations or CMS Parties.

4.5. Mitigating fisheries mortality

While international trade is a key driver of mobulid mortality that must be addressed through a combination of trade regulations to curb demand and domestic species protections, reducing mobulid mortality also requires a reduction in the impact of incidental fisheries. Although knowledge on best practices is growing, few mitigation actions have been implemented and the effectiveness of these strategies is unclear for many species and fisheries. Mitigation measures can be classified into two main categories: (a) limiting incidental catch, and (b) reducing at-vessel and post-release mortality. The former may include (1) permanent or seasonal gear controls to regulate setting nets or lines in key habitats, (2) input controls (limits on fishing effort), (3) output controls (limits on allowable incidental catch), and (4) gear modifications to improve selectivity, such as Bycatch Reduction Devices (BRDs). Methods to reduce at-vessel and post-release mortality include promoting escape from gear, live-release, and best-practices for handling onboard and release (Gilman et al., 2022; Cronin et al., 2023; Murua et al., 2025).

Zero-bycatch retention quotas for mobulids or retention bans, often explicitly required by tRFMOs, or implicit in domestic protections, should be clearly stated in NPOAs, communicated to fishers, and appropriate live-release measures disseminated (Cronin et al., 2023; Stewart et al., 2024). To monitor catch and compliance, onboard observer coverage and the use of electronic monitoring systems (EMS) should be increased in LV fisheries, and EMS introduced in SV fisheries, where possible. EMS are currently being trialed in SV fleets off Ecuador (TUNACONs), and off East Java, Indonesia (Salim, pers. comm.). Where introduced, gear-specific measures to reduce mortality, such as BRDs, should always be combined with monitoring tools so that their efficacy, effects on other species fished, and affordability can be assessed within the local context before incentivising uptake (SI11).

Gear soak time and handling time are key determinants of post-release mobulid survival. For example, AVM is high in purse seines and post-release survival tends to be low (20–74 %). However, the latter could increase by >80 % if mobulids are properly handled and released within 3 min of bringing onboard, although survivorship varies across species (Stewart et al., 2024). Preliminary studies from SV drift gillnets show generally high survival rates for *M. mobular*, likely reflecting relatively short soak times (~1–4 h) (Laglbauer, pers. comm.). When gillnets are left to soak for extended periods, survival declines drastically; for example, 74 % of *M. eregoodoo* are dead upon retrieval from bather-protection nets off eastern Australia (Broadhurst and Cullis, 2020). Net gears restrict the movement of mobulids through entanglement, which lowers oxygenation and compromises survival (Stewart et al., 2024). Regulating the use of gillnets in critical habitats for mobulids, especially drift gillnets of larger dimensions (with extended soak times) and set gillnets, is therefore a priority. In contrast, longlines have lower AVM rates and are more selective, usually hooking larger mobulid species that take fish and cephalopod baits (i.e., *M. birostris*, *M. tarapacana*, and *M. mobular*) (Martin, 2020). This may result in higher survival rates (Beerkircher et al., 2008; Coelho et al., 2012; Mas et al., 2015), but LV longline fishery impacts on mobulids require further attention, alongside impacts of purse seines.

Effective conservation of mobulid rays requires a mix of area-based and community-driven management approaches. Area-based measures—like seasonal or permanent fishing restrictions—can significantly reduce bycatch, but their success depends on context, especially in multi-gear fisheries and lower-HDI countries where enforcement is challenging and socio-economic impacts must be minimized. In LV fleets, real-time communication can help avoid bycatch (Gilman et al., 2006), while SV fisheries often need permanent or seasonal closures based on species' critical habitats (e.g., for breeding or feeding) (Henderson et al., 2018; Kyne et al., 2023).

The IUCN's Important Shark & Ray Areas (ISRAs) identify vital mobulid habitats, yet only a small portion overlaps with protected areas (Hyde et al., 2022; Sciberras et al., 2024). Prioritizing ISRAs alongside Ecologically and Biologically Significant Areas (EBSAs) and Key Biodiversity Areas (KBAs) within broader management strategies is crucial, and should be complemented by integrated fisheries regulations and trade controls (García-Rodríguez et al., 2025). Marine Protected Areas (MPAs) can benefit both mobulids and local communities through spillover and eco-tourism, though success hinges on overlap with critical areas and migratory corridors, adaptive design, monitoring and strong enforcement (Setyawan et al., 2022; Hall et al., 2023). For instance, in the Raja Ampat MPA, home to a nursery site for *M. alfredi*, community engagement and robust monitoring have contributed to significant population growth and increased pregnancy rates for the species (Setyawan et al., 2022).

In parallel, improved small-scale fisheries (SSF) management through Territorial Use Rights (TURFs), co-management, and other community-based approaches offers equitable and effective alternatives or complements to MPAs, especially in data-poor regions (Biodiversa, 2022; Bennett et al., 2022). The Convention on Biological Diversity now recognises such locally-led models (OECMs) as valid conservation tools (CBD, 2018; Ban et al., 2020). Successful examples from Latin America, Southeast Asia, and the Mediterranean show that involving communities in governance, granting access rights, and offering market incentives encourage stewardship and compliance (Ban et al., 2020; Gill et al., 2023; Basurto et al., 2024). Additional tools like participatory research, education, certification schemes, Fishery Improvement Projects and diversification programs—though underused for mobulid rays—show promise for implementing area-based conservation (Booth et al., 2020; Sánchez-Jiménez et al., 2021; Shidqi et al., 2025).

4.6. Improving international management policy

Except for Peru, all major mobulid fishing nations contribute to the gill plate trade (i.e., Sri Lanka, India, Indonesia, and Myanmar). Jointly, these four countries also dominate global landings, market higher-priced mobulid meat and gill plates than observed elsewhere (Palacios et al., 2025), and are the likely source of most traded mobulid gill plates. However, varying levels of customs control and access to established trade routes, and other factors, likely affect opportunities for exporting mobulid products to intermediary (i.e., Thailand) and consumer countries (i.e., China, Hong Kong, Singapore) (Palacios et al., 2025). Other exporters (i.e., Yemen, Somalia, Sudan) appear in trade databases or expert reports; these countries are priorities for fishery surveys (Palacios et al., 2025).

Evidence of increasing threats to mobulids has led to improved international, regional and domestic level policy frameworks. Globally, listing on CITES Appendix II, in 2013 and 2016, mandates international trade regulation (including of catches in ABNJ), but does not affect domestic use, while listing on Appendix I of CMS in 2014 requires signatory states to protect all mobulids. The extent to which international policies can help (directly or indirectly) reduce mortality depends on national implementation, and the context in which mobulids are landed. Targeted and/or retained incidental catch, the main source of mortality, is strongly influenced by legal and illegal international trade demand for mobulid gills, although domestic consumption of meat is also important in some countries. The CITES Appendix II listings require exporting countries to certify that the fisheries supplying trade are legal (Management Authorities prepare legal acquisition findings, LAF), sustainable (Scientific Authorities prepare NDFs), and traceable; a process that should support management measures adopted by tRFMOs. However, without domestic legislation, management and compliance measures, unsustainable trade is likely to continue and implementation by some CITES Parties has been inadequate (Haque et al., 2021).

The enforcement and compliance mechanisms of CITES, CMS, and regional seas conventions differ (Palacios et al., 2025). CITES imposes the strictest regulatory measures with legal enforcement mechanisms, including permit systems and sanctions for non-compliance (Humphries, 2013). However, despite these measures, evidence from trade databases, market surveys, and expert interviews reveals a widespread trade network involving mobulid gill plates and meat, with trade hubs in Asia and Africa consistently supplying international markets, particularly mainland China and Hong Kong (TRAFFIC, 2016; Haque et al., 2021; Palacios et al., 2025). Mobulid products continue to be exported at unsustainable rates by multiple key fishing nations, for example in Sri Lanka and Myanmar (CITES Trade database, 2024; Palacios et al., 2025; Ko Gyi et al., 2025 [In prep.]). Moreover, in India, trade occurs under NDF assessments despite evidence of mobulid catch declines, and despite tRFMO management measures precluding legal acquisition requirements (Thomas et al., 2022; CITES Trade database, 2024). Better compliance monitoring of mobulid fisheries and landings could improve the capacity of priority countries to enforce CITES (also CMS and tRFMO measures) by intercepting catch and products before they enter the supply chain (Palacios et al., 2025). Given difficulties in tracing and controlling trade, and proving legal acquisition and sustainability in NDF processes, adoption of a CITES Appendix I listing for mobulids is proposed to reinforce international regulatory frameworks, reduce market demand, and support existing CMS and tRFMO management measures toward improved conservation outcomes for these threatened species (TRAFFIC, 2016; Palacios et al., 2025).

4.7. Limitations

We acknowledge the importance of using the best-available data to guide conservation, and some significant limitations in our analysis. Mobulid catch and mortality are likely underestimated due to reliance on official reports and literature, which often lack species-level detail and consistent taxonomy (Cronin et al., 2023). Data gaps stem from poor national reporting and limited transparency in tRFMO databases, hindering stock assessments and trend monitoring. For instance, while fisheries in the WCPFC catch more than half of the world's tuna (Hare et al., 2021), mobulid catch in the area couldn't be linked to specific flag states, restricting country comparisons (Tremblay-Boyer and Berkenbusch, 2020). Only 12 countries report mobulid landings to the FAO, and tRFMO data cover just 14 (ICCAT, 2024; IOTC, 2024; FAO, 2024). Although more nations have reported since 2016, reported catches dropped by 87 % by 2023, possibly masking local declines. Underreporting and low observer coverage, especially in small or unmonitored fleets, raise concerns about the accuracy of fleet-level catch estimates (Cashion et al., 2019; Fowler et al., 2021; Peatman et al., 2023). Most LV data come from observed, compliant fleets, likely underestimating actual AVM and retention rates (Raje and Zacharia, 2009; Suuronen and Gilman, 2020; Thomas et al., 2022). Inconsistent timeframes across datasets further limit accuracy, so current mobulid catch/mortality rates may differ from values reported here. Critically, data are missing from many mobulid-catching nations, especially in Africa, likely skewing Atlantic basin estimates. These countries and others highlighted as data-deficient should be prioritized for improved data collection to support more accurate global assessments.

Identifying mobulids to species level is challenging in fast-paced landing sites or, in particular, onboard LV vessels where specimens may not be closely inspected, even for trained observers. This can result in widespread species misidentification or catches that are grouped under broad categories unlikely to reflect species diversity in fisheries (Martin, 2020; Cronin et al., 2023). For example, the contribution of mantas (unidentified species) and *M. birostris* to LV catch was likely overestimated across multiple fleets (Martin, 2020; Cronin et al., 2023;

SI3). There are similar limitations and challenges in species-specific data in SV fisheries, where data are usually obtained from landing surveys, limited by capacity, and catch is underestimated in some countries (Fernando and Stewart, 2021). A lack of mobulid fisheries monitoring at key landing sites in coastal areas potentially suitable for mobulids (i.e., Yemen, Iran, and Malaysia) may have skewed mortality toward better monitored countries, or locations. Additionally, for data based on weight conversions, catch could be underestimated in areas where regional mean mobulid weights are above those of landed specimens (i.e., nursery areas).

Improving mobulid (and other bycatch) monitoring requires disseminating ID guides tailored to fisheries contexts, and applying new AI and genetic tools that have emerged to identify species of high commercial value in several fisheries (i.e., tuna). Existing fisheries data programs should be leveraged to collect CPUE data for mobulids in SV and LV fleets. Understanding CPUE of mobulids and other target fishes in SV fisheries is not only essential to assess trends, but also to understand their contribution to fishers' income relative to other species. Geospatial catch data is crucial to understand habitat overlap with target fish catches and reduce mobulid bycatch by adjusting fishing locations. Finally, observer coverage remains low, particularly in SV and some LV fleets, allowing illegal and unreported activities to persist (Worm et al., 2024). As noted above, expanding EMS can significantly boost data collection where human observers are not feasible, particularly in smaller vessels, including in offshore longline undertaking long trips at sea.

5. Conclusions

To address the greatest threat to mobulids globally, namely, targeted catch and retention in non-selective gear, we recommend:

(1) legal protection under wildlife legislation, especially in high mortality-risk priority countries,
(2) retention bans and zero incidental catch retention quotas under fisheries legislation and NPOAs (if not explicitly mentioned in wildlife legislation), to provide the policy framework for:
(3) incidental catch mitigation through live-release, using appropriate handling and release guidelines, particularly limiting handling time below 3 min,
(4) avoidance of critical habitats through (a) permanent measures to avoid catching mobulids where year-round catch occurs, (b) spatio-temporal measures where bycatch is seasonal, and (c) employing mitigation techniques to predict and avoid the presence of mobulids, and banning gear sets on mobulid schools (SI11; Fernando and Stewart, 2021; Cronin et al., 2023; Stewart et al., 2024).

To reduce demand and improve compliance, which will also discourage mobulid retention, we recommend:

(1) uplisting mobulids to CITES Appendix I,
(2) training of onboard observers to monitor retention and best-practices (i.e., identification, and safe handling and release), and port and customs officials to facilitate enforcement,
(3) engaging with fishers and other local stakeholders to promote alternative approaches to achieve no net losses or positive outcomes, including participation in the development and management of fisheries or area-based measures (Booth et al., 2019; Guirkinger et al., 2021).

CRediT authorship contribution statement

Betty J.L. Laglbauer: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Nidhi G. D'Costa:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Joshua D. Stewart:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Marta D. Palacios:** Writing – review & editing, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Melissa Cronin:** Writing – review & editing, Project administration, Methodology, Investigation, Conceptualization. **Daniel Fernando:** Writing – review & editing, Validation, Methodology, Investigation, Conceptualization. **Nerea Lezama-Ochoa:** Writing – review & editing, Project administration, Methodology, Conceptualization. **Asia O. Armstrong:** Writing – review & editing, Project administration, Methodology, Conceptualization. **Rima W. Jabado:** Writing – review & editing, Validation, Investigation. **Sarah Fowler:** Writing – review & editing, Validation, Investigation. **Julia M. Lawson:** Writing – review & editing, Validation, Methodology, Investigation. **Olga Koubrak:** Writing – review & editing, Validation, Methodology, Investigation. **Jefferson Murua:** Writing – review & editing, Validation, Methodology. **Thanda Ko Gyi:** Writing – review & editing, Validation, Methodology, Investigation. **Divya Karnad:** Writing – review & editing, Validation, Methodology, Investigation. **Mayuri Chopra:** Writing – review & editing, Validation, Methodology, Investigation. **Giuseppe Notarbartolo-di-Sciara:** Writing – review & editing, Validation, Methodology, Investigation. **Joshua Rambahiniarison:** Writing – review & editing, Validation, Methodology, Investigation. **Don Croll:** Writing – review & editing, Validation, Project administration, Methodology. **Stefany Rojas:** Writing – review & editing, Project administration, Methodology, Investigation. **Fahmi:** Writing – review & editing, Validation, Investigation. **Joanna L. Harris:** Writing – review & editing, Validation, Investigation. **Alifa Binthe Haque:** Writing – review & editing, Validation, Methodology. **Hilario Murua:** Writing – review & editing, Validation. **Juan Carlos Pérez-Jiménez:** Writing – review & editing, Validation. **Emily Humble:** Writing – review & editing, Validation, Methodology. **Ellen Barrowclift:** Writing – review & editing, Validation, Data curation. **Muhammad G. Salim:** Writing – review & editing, Validation, Investigation. **Godefroy De Bruyne:** Writing – review & editing, Validation, Investigation. **Issah Seidu:** Writing – review & editing, Validation, Investigation. **Luis A. Zambrano-Vizquel:** Writing – review & editing, Validation, Investigation. **Katrina Davies:** Writing – review & editing, Validation, Methodology. **Muhammad Moazzam Khan:** Writing – review & editing, Validation, Investigation. **Nayara Bucair:** Writing – review & editing, Validation, Investigation. **Jeannie Johnson:** Writing – review & editing, Methodology, Investigation, Data curation. **Ghofrane Labyedh:** Writing – review & editing, Validation, Investigation. **Aristide Takoukam Kamla:** Writing – review & editing, Validation, Investigation. **Karen Fuentes:** Writing – review & editing, Validation, Investigation. **Rebecca Carter:** Writing – review & editing, Validation, Methodology, Investigation, Funding acquisition, Data curation. **Nuno Barros:** Writing – review & editing, Validation, Methodology, Funding acquisition. **Guy M.W. Stevens:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Ethical approval

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Declaration of competing interest

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Appendix A. Supplementary data

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Data availability

Data will be made available on request.

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