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Harnessing stakeholder knowledge for the collaborative development of Mobulid bycatch mitigation strategies in tuna fisheries

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Manta and devil rays (Mobulids) face several immediate threats, including incidental capture in industrial tropical tuna fisheries. As a result, efforts have emerged to avoid or mitigate Mobulid bycatch in these fisheries. However, many mitigation efforts fail to incorporate fisher expertise from the outset, potentially leading to interventions that are not viable. Here, we combine survey and focus group data to synthesize knowledge of Mobulid bycatch and mitigation ideas in Eastern Pacific Ocean purse seine fisheries. Primary obstacles for mitigating Mobulid bycatch, according to respondents, are: (1) an inability to sight Mobulids before capture, (2) the lack of specific equipment on board, and (3) the difficulty of releasing large individuals; we suggest that the latter two can be addressed by simple operational modifications. We also find that Mobulids are most likely to be sighted by fishers after capture, suggesting that this is an important time in the fishing operation for bycatch mitigation interventions that ensure Mobulids survive capture. To address this, we share creative ideas brought by fishers for avoidance of Mobulids. This study provides a model of how to incorporate stakeholder input in the design of bycatch technology in large-scale fisheries and could inform similar efforts around the world.

Keywords: bycatch mitigation, collaboration, elasmobranch, mobulid rays, technology.

Introduction

Manta and devil rays, collectively known as Mobulids, are a group of threatened, yet poorly studied filter-feeding batoid rays distributed globally in tropical and subtropical waters (Couturier *et al.*, 2012). While few adequate population estimates for Mobulids exist, empirical and anecdotal evidence suggests that their populations are declining worldwide (Ward-Paige *et al.*, 2013; Lewis *et al.*, 2015; Haque *et al.*, 2021). Due to these declines and their extremely slow population growth rates and low fecundity (Couturier *et al.*, 2012; Dulvy *et al.*, 2014; Pardo *et al.*, 2016), all 10 Mobulid ray species are now listed as "Vulnerable" or "Endangered" with declining population trends on the IUCN Red List and recent ecological risk assessments (Dulvy *et al.*, 2021; Griffiths and Lezama-Ochoa, 2021; IUCN, 2021). As a result, a growing body of scientific research and conservation efforts have focused on identifying major drivers of Mobulid population declines and opportunities to halt or reverse them (Stewart *et al.*, 2018).

Direct fishing coupled with incidental bycatch in both small- and large-scale fisheries have been identified as immediate conservation concerns for Mobulids (Oliver *et al.*, 2015; Acebes and Tull, 2016; Alfaro-Cordova *et al.*, 2017). Fishers target Mobulids for meat in at least 12 countries, and for their gill plates for the Asian medicine trade in some regions (Croll *et al.*, 2016; Lawson *et al.*, 2017). Reports of the full scale of direct fisheries are not available for many regions, but one estimate suggests global catch was, at least recently, as many as 97 000 individuals annually (Heinrichs *et al.*, 2011). At least 21 small-scale fisheries, particularly those using gillnets, driftnets, trawls, and longlines incidentally catch Mobulids in 15 countries (Croll *et al.*, 2016; Alfaro-Cordova *et al.*, 2017). Among industrial fisheries, longline vessels appear to catch relatively few Mobulids, though significant uncertainty remains about the scale of Mobulid capture in longlines (Mas *et al.*, 2015). In comparison, tropical tuna purse seiners have been identified as an important source of Mobulid bycatch, capturing an estimated ~13 000 individuals per year, though these captures do not translate directly into mortalities, as most individuals are released dead or alive after capture (Hall and Roman, 2013; Croll *et al.*, 2016; Gray and Kennelly, 2018).

Tropical tuna purse seine fisheries are managed by five tuna Regional Fisheries Management Organizations (tRFMOs), international governance bodies that set fishery management

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Table 1. Current conservation and management measures adopted for Mobulids rays by tRFMOs.

Management body	Year adopted	Requirements
Inter-American Tropical Tuna Commission (IATTC)	2015	Landing, retention, and transshipment ban;encourages best handling practices while prohibiting others [C-15–04]
International Commission for the Conservation of Atlantic Tunas (ICCAT)	NA	NA
Indian Ocean Tuna Commission (IOTC)	2019	Setting, landing, retention, and transshipment ban; requires the immediate release and use of best handling practices [19/03]
Western and Central Pacific Fisheries Commission (WCPFC)	2019	Setting, landing, retention, and transshipment ban; encourages best handling practices [2019–05]
Commission for the Conservation of Southern Bluefin Tuna (CCSBT)	*Adheres to all above measures while fishing in Convention Areas*	

and conservation regulations for country members targeting tuna and tuna-like species. In response to these high rates of Mobulid bycatch, over the past 5 years all but one of the major tRFMOs have adopted conservation measures that ban the landing, retention, and transshipment of Mobulids (Table 1). These measures also prohibit harmful handling practices, particularly used for large individuals, like using gaff hooks and cutting holes in the bodies of large individuals that are difficult to lift (Poisson *et al*., 2014; Hutchinson *et al*., 2017).

Though these measures may reduce the retention of Mobulids, retention bans alone are unlikely to significantly reduce mortality (Tolotti *et al*., 2015), as species-specific post-release mortality rates for Mobulids are not yet known (Stewart *et al*., 2018). Currently, post-release mortality is assumed to be 100%, lacking evidence to the contrary and given previous harmful handling practices (Hall and Roman, 2013; Griffiths and Lezama-Ochoa, 2021). Yet, some preliminary evidence suggests that post-release mortality is highly variable and dependent on species, ontogeny, region, and gear, but is likely to be high for some species (Francis and Jones, 2017). Considering these uncertainties, the feasibility and effectiveness of existing conservation measures for Mobulids in tRFMOs also remain unclear, and efforts to identify the most effective interventions are needed.

Given these conservation concerns, an ecological risk assessment was recently conducted for the most globally distributed and frequently captured Mobulid species, the spinetail devil ray (*Mobula mobular*), in the Eastern Pacific Ocean (EPO; Griffiths and Lezama-Ochoa, 2021). The assessment concluded that reducing post-release mortality rates, combined with the implementation of spatial and temporal management, were most likely to reduce the population-level impacts of purse seine bycatch. This finding is promising, given that improving handling and release methods may be more feasible and cost-effective than other options (Soykan *et al*., 2008), and that spatiotemporal management may substantially reduce the probability of bycatch interactions (Hazen *et al*., 2018). Beyond conservation threat, there is strong interest from the tuna-fishing industry to address Mobulid bycatch, as it has been identified as a barrier preventing tuna fisheries from obtaining major sustainability certifications (Seafood Watch, 2021).

Mobulid bycatch in the EPO

Presently, purse seining for tropical tuna is one of the most technologically advanced fisheries in the world (Scott and Lopez, 2014; Moreno *et al*., 2019). Purse seiners mainly target skipjack (*Katsuonus pelamis*), yellowfin (*Thunnus albacares*), and bigeye tuna (*Thunnus obesus*), and use sophisticated technology like satellite-linked echo-sounder buoys, bird radars, sonars, and long-range binoculars to detect tuna schools (Lopez *et al*., 2014). In the EPO (50°S–50°N and coastline −150°W), a highly productive and biodiverse region, purse seine fleets conduct sets on tuna associated with dolphins (dolphin sets), tuna associated with floating objects (either natural objects or man-made objects deployed by fishers, called fish-aggregating devices or FADs) and sets on unassociated tuna schools (school sets). The Inter-American Tropical Tuna Commission (IATTC) is responsible for the management of tuna and tuna-like species in the EPO, with an average annual catch of about 600 000 tons of tuna in recent years (IATTC, 2021).

A total of five species of Mobulids are captured in the EPO tuna purse seine fishery: *M. mobular, M. munkiana, M. birostris, M. thurstoni,* and *M. tarapacana*. Bycatch of these species shows interannual variability, but overall their capture has decreased from 5022 total recorded individuals in 2010 to 705 in 2018, despite increases in purse seine fishing effort in the region (Griffiths and Lezama-Ochoa, 2021). The spatial distribution of Mobulid bycatch in the EPO (Figure 1) is associated with areas of high productivity, including off the coasts of Peru, the Galapagos Islands, and the Costa Rica dome (Lezama-Ochoa *et al*., 2019).

Tuna purse seine fishing operation

The industrial purse seine gear consists of a large net, approximately 1500–2000 m long and 150–350 m construction depth (fishing depth is around 50–60% of that figure), used to encircle a tuna school and then cinched at the bottom (Hall and Roman, 2013). Notably, until the purse seine is closed—a process that takes about 30 min—the tunas and non-target species can still dive below the net or the purse seine vessel and escape. The net is then pulled aboard the vessel with a hydraulic power block. When most of the purse seine has been retrieved, the catch is concentrated within a restricted area along the port side of the vessel, a process referred to as “sacking up,” which takes about 1 h. The catch is then harvested from the purse seine using a large scoop net called the brailer, a process referred to as “brailing”; 5–10 tons of fish are taken on board in each brail (Pravin, 2002). The duration of the brailing process is highly variable, and can range roughly from 30 min to more than 3 h. Factors that influence the duration include: set type (e.g. school sets mainly catch tuna, while FAD sets often have to release more bycatch); the amount of tuna

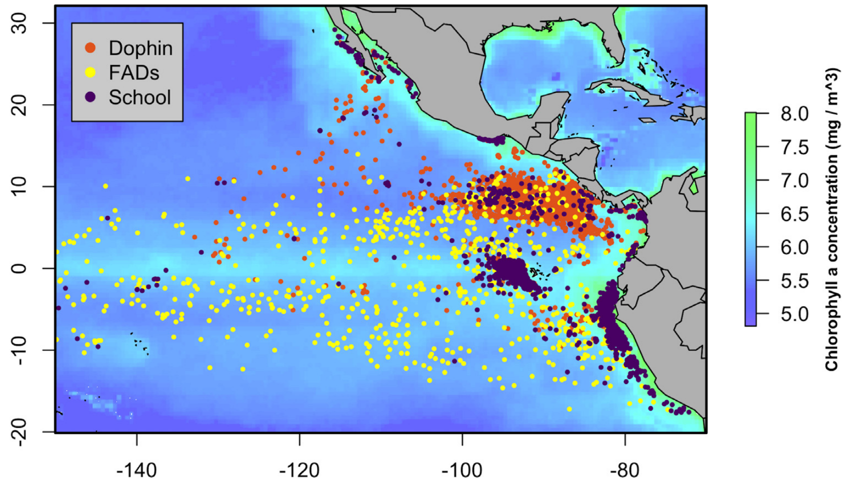

Figure 1. Mobulid ray bycatch in the EPO from 1993 to 2014. Dots represent the location of a Mobulid bycatch event reported in the tuna purse seine fishery. Color indicates purse seine set type (orange: dolphin-associated sets, yellow: FAD-associated sets, and purple: free swimming school sets). Primary production data from Global Marine Environment Datasets (http://gmed.auckland.ac.nz/). Adapted from Lezama-Ochoa *et al.* (2019).

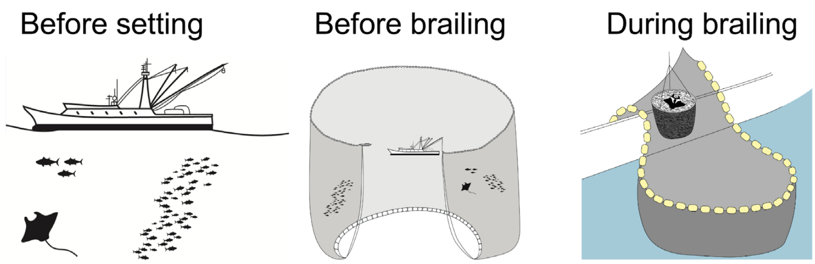

Figure 2. Stages of purse seine fishing during which bycatch mitigation efforts could focus to reduce Mobulid capture and mortality.

captured (the capacity of the brail net is 2–10 tons, and more tuna takes longer to brail); weather/current conditions can make the brailing process complicated (wind, waves, and so on); technology related to the brailer; and technique and experience of the captain and fishers (Hall and Roman, 2013; Poisson *et al.*, 2014). Roughly, this process can be grouped into three stages on which mitigation efforts could focus: (1) before setting the purse seine net, when animals may be swimming at the surface and sighted and avoided, (2) before brailing, when animals are encircled by the net but may be released directly from the seine, and (3) during brailing, when animals may be released from the seine net with the brailer or from the deck using other release methods (Figure 2).

Identifying opportunities to avoid or reduce Mobulid mortality throughout the fishing operation requires additional information to prioritize future research areas (Murua *et al.*, 2020). For example, whether interventions would be most effective before the purse seine net is set, while rays are still circled in the net, or after they are brought on deck depends largely on how effectively the fishing vessel crew can intervene at different stages of the capture process (Grande *et al.*, 2019a, b). Because Mobulids are obligate ram ventilators and must constantly pass water over their gills, the window to ensure or increase their post-capture survival is considered short (Francis, 2014). A better understanding of the different stages of the interaction between purse seine gear and Mobulids would aid in the development of rapid release mitigation actions and technologies to increase post-release survival for Mobulids (Grande *et al.*, 2019b).

These data gaps, combined with conservation and sustainability concerns about the impacts of Mobulid bycatch, have triggered interest from scientists, fishery managers, non-profit organizations, fishers, and industry representatives in developing innovative and effective bycatch mitigation technologies tailored to Mobulid bycatch on purse seine vessels (Murua *et al.*, 2021). However, historically bycatch mitigation efforts have not typically involved input from fishers, and as a result many novel bycatch mitigation technologies have low rates of voluntary uptake by fishers (Eayrs and Pol, 2019). Failure to meaningfully incorporate fisher perspectives in the development and production of fishing technology can lead to inefficient or ineffective technologies that are less likely to be implemented and/or more likely to fail (Hall and Mainprize, 2005; Campbell and Cornwell, 2008).

The collaborative approach

Collaborative development (sometimes referred to as "co-production"), or the participatory and iterative production of knowledge by scientists and stakeholders (Palomo *et al.*, 2016; Miller and Wyborn, 2020), has been proposed as a solution to incorporate fisher perspectives into effective fisheries management innovations (Djenontin and Meadow, 2018; Chambers *et al.*, 2021). In fisheries, failure to consider fishers' knowledge in fishery and aquatic conservation research may risk missing important solutions that are obvious to fishers, but not to managers or scientists (Johannes *et al.*, 2000). In the case of large-scale tuna fisheries that operate in the open ocean, collaborative development is especially valuable, as scientific research in wide ranging fishing grounds is expensive due to the need to hire research vessels and the time needed for scientists to be at sea (Moreno *et al.*, 2007). More specifically for megafauna bycatch, participatory research involving surveys, workshops, focus groups, and other information gathering and sharing methods between fishers and scientists has yielded to date some of the most successful developments in mitigation technologies including turtle excluder devices (TEDs), tori lines, Medina panels, and the backdown procedure, to name a few (Hall, 2007; Jenkins, 2010; Johnson, 2010). To co-develop Mobulid bycatch mitigation strategies in tropical tuna purse seine fisheries, we conducted a qualitative and quantitative investigation of fisher knowledge of, perceptions about, and ideas to address threatened species bycatch in large-scale tuna fisheries. We surveyed 170 stakeholders from tuna purse seine fisheries in the EPO to gain insights about their (1) general perceptions and knowledge of Mobulid bycatch, (2) major challenges to Mobulid bycatch mitigation, and (3) innovative ideas to reduce capture and mortality across the fishery. We supplement this data from discussions with three large, structured focus groups involving 130 stakeholders on the topic. We propose these results as a guide for the development of bycatch mitigation technology for Mobulids in large-scale tuna fisheries, and an example of collaborative development of bycatch solutions.

Methods

We combined surveys and focus groups to gather and synthesize quantitative and qualitative information from fishery stakeholders operating in the EPO.

Participants

We requested participation from stakeholders who have experience at sea aboard a tuna purse seine vessel in the EPO, and thus can comment on the operational process involved with capture of Mobulids (rather, for instance, than its conservation or management implications). Participants included in this study were fishers (i.e. captains, deckhands, and navigators) and fishery observers. We surveyed fishing crews operating from Spanish and Ecuadorian flagged vessels. Because terminology for fishing role/occupation varies slightly between these two fleets, we grouped respondents into occupational categories. For instance, in the Spanish vessels, fishing masters are solely in charge of the long-range planning and short-term decisions on when, where, and how to proceed with fishing operations, while captains and navigators are in charge of administrative paperwork and assist in fishing operations (Moreno *et al.*, 2007). In Ecuadorian vessels, both roles are filled by the captain (Supplementary Table S1).

Survey design and distribution

Survey questions were grouped into four sections: (1) respondent demographics, (2) timing of Mobulid capture during gear retrieval, (3) perceptions of Mobulid bycatch, and (4) invitation for open-ended ideas for their avoidance, mitigation, and release (Table 2). Surveys were distributed in Spanish and results were translated by an independent translator service with experience in language peculiar to tuna fisheries before analysis to prevent bias in the translation of the answers. Because of travel restrictions due to the COVID-19 pandemic, we distributed some surveys via the online platform Survey Monkey (UCSC IRB Protocol #HS3816) from January to September 2021, and some in person during a 3-d tuna fisher capacity-building workshop in Manta, Ecuador in September 2021. Respondents read and agreed to a consent form prior to completing the survey and were instructed that there was no need to respond if a given question was regarded as sensitive, as no information was preferable to misinformation.

To understand how different occupational roles may affect survey answers, we grouped respondents into three broad categories of occupational role: (1) fishing crew, which included fishers/deckhands; (2) managerial crew (referred to as captains, skippers, navigators, and officials in the Ecuadorian-flagged vessels; and fishing masters, captains, and officials in Spanish-flagged vessels); and (3) fishery observers (Supplementary Table S1). We used these categories for grouping respondents based on their different roles, experience, expertise, and physical position during the purse seine sets and bycatch handling procedure. For instance, fishing crew generally handle or interact with the catch from the deck or a nearby location, while managerial crew make decisions about when, where, and how to set the net, and receive information from different members of the crew before and during the fishing operation. Finally, we grouped fisheries observers separately as they do not generally have the tools and experience that fishers possess to assess the presence of a Mobulid, but they may have more time or a different vantage point from which to focus on bycatch species' presence and fate compared to the crew, who may be more focused on the fishing operations. We additionally examined the responses of some subgroups (e.g. helicopter pilots), who may have a unique perspective on bycatch. We grouped respondents by experience into one of three categories: junior (1–9 years fishing experience), middle (10–19 years), and senior (20 or more years). Finally, we grouped respondents by vessel flag to account for patterns in answers due to different fishing strategies by different fleets. In cases where a participant did not respond to every question, we excluded their response from the analysis of that question (thus not all questions have the same number of respondents). We used the *dplyr* package in R software version 1.4.1717 to clean and analyze quantitative data, and the *likert* package in R to analyze data about knowledge of Mobulid presence during different stages of capture. We conducted a Shapiro test for normality, which indicated that the data did not follow a normal distribution. Thus, we used Kruskal–Wallis tests to identify significant differences between independent responses. For those groups where significant differences were found, *post hoc* paired Wilcoxon tests were used to identify differences between paired answers.

Finally, for open-ended questions about bycatch mitigation, we categorized ideas that are currently in use or not in the EPO, based on current practices observed in the fishery. We used a simplified version of the mitigation hierarchy framework (Milner-Gulland *et al.*, 2018; Booth *et al.*, 2019) for megafauna bycatch to qualitatively categorize mitigation ideas into three bins, relative to the chronology of the fishing operation: (1) before capture (avoidance), (2) pre-deck (mitigation), and (3) on deck (mitigation).

Focus groups

We held three large, structured focus groups with fishing and managerial crew in Manta, Ecuador, during September 2021. Each focus group lasted approximately 35 min and consisted

Table 2. Survey questions included in this study.

Category	Question	Answer type
Demographics	What is your role/occupation?	Multiple choice
	How many years of fishing experience do you have in the Pacific?	Numeric
	What method of fishing do you primarily use?	-FADs-Dolphin sets-Unassociated set
Timing of Mobulid bycatch	Can you ever tell whether there is a Mobulid in the area **before** setting the net?	Likert scale: never, seldom, sometimes, always
	If you responded yes to the previous question, please indicate the type of information you use to determine the presence of encircled Mobulid(s):	Open-ended
	After encirclement, how often do you realize there is a Mobulid in the net **before** brailing?	Likert scale: never, seldom, sometimes, always
	How often do you realize there is a Mobulid in the net **during** brailing?	Likert scale: never, seldom, sometimes, always
Perceptions of Mobulid bycatch release	Is it difficult for you to release Mobulids? Why? (Select all that apply)	Multiple choice:-Too heavy/large/difficult to brail-difficult to handle on deck-Too heavy/difficult to release from deck-Increases brailing time-Increases handling time on deck-Dangerous for the crew to release them-Damages fishing gear-Loss of fishing time-Need to have specific gear on board for handling and release
	Once on board, how do you normally release Mobulids?	Multiple choice:-Manually-cargo net-using a brailer net-using a modified brailer net-stretcher-other
	When an observer has to measure and deploy a tag on a Mobulid, does that cause a problem?	Yes/No
	Do you know that these ways of releasing Mobulids should be avoided?	Yes/No(images of prohibited methods included)
Release and mitigation ideas	Do you have any idea of how to avoid capturing Mobulids?	Open-ended
	Do you have any idea of how to release Mobulids from the purse seine net?	Open-ended
	Do you have any idea of how to release Mobulids from the brailer?	Open-ended
	Do you have any idea of how to release Mobulids from the vessel deck?	Open-ended

of roughly 30–50 participants, all of whom had experience on board a tuna purse seine vessel as a crew member, observer, captain, or other related occupation. Focus groups were facilitated in Spanish by a moderator and structured with pre-written questions, though participants were encouraged to respond freely. For each focus group, the facilitator led discussion about the following four topics: (1) general information about Mobulid bycatch, (2) major obstacles to mitigating Mobulid bycatch, (3) education and awareness of Mobulids, and (4) current and proposed bycatch mitigation methods (Table 3). The facilitator asked the same questions during each focus group in the same order. Focus group responses were recorded, translated into English by the same translator who translated the surveys, and transcribed. We conducted a classical content analysis to identify major themes for each section, following methods described in Krueger and Casey (2014). Briefly, this included a preliminary reading of the focus group transcripts to produce a conceptual map of common themes, followed by a second reading to identify and code sub-themes within the larger themes. We used the software NVivo (Version 12) to conduct the coding.

Results

Survey results

Demographics

After excluding two surveys for which no questions were answered, we surveyed 170 stakeholders, most of whom were crew members ($n = 84$), followed by managerial crew ($n = 61$) and fishery observers ($n = 20$; Table 4). A total of two respondents did not provide their occupation. Respondents fished in Ecuadorian-flagged vessels ($n = 125$) and Spanish-flagged vessels ($n = 45$) operating in the EPO, and some respondents worked on the same fishing vessels as one another. All respondents said that they primarily fished using FADs.

Timing of Mobulid bycatch

When asked about when Mobulids were visible in the event of a capture, the proportion of respondents who said they "always" or "sometimes" knew a Mobulid was present was significantly greater for each stage of the fishing operation since approaching the tuna school (Figure 3; Kruskal–Wallis test, $p < 0.001$, pairwise Wilcoxon rank-sum test, $p < 0.001$; Supplementary Figure S1). Before setting the purse seine net, 12% of respondents ($n = 20$) said that they "always" or "sometimes" knew a Mobulid was present. Of those respondents who said that they could "sometimes" or "always" identify a Mobulid *before* setting the net, 70% ($n = 14$) reported that they did so by using visual identification from the vessel deck to confirm its presence.

During the next step, before brailing (after the Mobulid has been encircled by the net), 33% of respondents ($n = 53$) were "always" or "sometimes" aware of a Mobulid present. Finally, during the last step, brailing (when the catch is being brought on deck), 66% respondents ($n = 108$) were "always"

Table 3. Topics and questions asked of each focus group.

Theme	Questions
General information about Mobulid bycatch	• What is your perception of Mobulids in general? • Approximately how often do you come across Mobulids in your fishing? Once a week, month, year, etc.? • If you were fishing then, think back to 20 years ago. Did you catch the same amount of Mobulids as now? Was there a difference? • How about 10 years ago? Did you catch the same amount of Mobulids as now? Was there a difference? • In general, have you noticed a change in the number of Mobulas you catch? How has it changed?
Major obstacles to mitigating Mobulid bycatch	• Are Mobulids difficult to release? If so, what characteristics make Mobulids difficult to release? Are some harder to release than others? • Do observers report the presence of Mobulids? If not, is it because they are only focused on tuna and do not report other species, or because they do not see them? • If spotters on top of the vessel were instructed to spot Mobulids, do you think it would be easier to tell of their presence before the set? • What could be done if the fishermen knew in advance that there is a large Mobulid in the net? Would knowledge of their presence help make release easier? • What is the normal method to release Mobulids? Do you use a different method if they are large?
Education and awareness of Mobulids	• Imagine that you have unlimited time and money. What would you do to try to reduce the bycatch of large animals like Mobulids? • In general, where do you get new information about bycatch animals like Mobulids? • In general, where do you get new information about fishing technology or techniques?
Current and proposed bycatch mitigation methods for Mobulids	• Do you know of any method/technology to avoid interactions with Mobulids? • When you make a change to the fishing vessel or operations specifically on bycatch, what is usually the cause of the change? • Have you ever made changes to the vessel or operations when a conservation measure does not require it? For example, change something in the equipment to lift a heavy animal? • If you've ever done this, make a change when it's not needed, how did you come up with it? Did you think of it yourself or did you hear it from someone else?

Table 4. Demographics of fishery stakeholders surveyed for this study.

	Junior ($N = 47$)	Middle ($N = 45$)	Senior ($N = 71$)	Overall ($N = 170$)
Position				
Fishing crew	19 (40.4%)	22 (48.9%)	41 (57.7%)	84 (49.4%)
Managerial crew	15 (31.9%)	17 (37.8%)	28 (39.4%)	61 (35.9%)
Observer	13 (27.7%)	4 (8.9%)	0	20 (11.8%)
Missing	0	2 (4.4%)	2 (2.8%)	5 (2.9%)
Flag				
Ecuador	27 (57.4%)	34 (75.6%)	60 (84.5%)	125 (73.5%)
Spain	20 (42.6%)	11 (24.4%)	11 (15.5%)	45 (26.5%)

or "sometimes" aware of a Mobulid, and no respondent said they were "never" aware of a Mobulid at this stage (Figure 3).

When examining responses by demographic groups, the participant's experience (junior, middle, or senior), role (managerial crew, crew, or observer), and flag (Spain or Ecuador) had a significant impact on the distribution of answers to almost all questions regarding timing of knowledge of Mobulid capture (Supplementary Figure S2, Kruskal–Wallis rank-sum test, $p < 0.05$). For example, junior respondents (< 10 years experience) were most likely to report identifying Mobulids before brailing ($p < 0.01$), and were slightly more likely than senior respondents to report identifying Mobulids during brailing, although that difference was non-significant ($p = 0.06$; Supplementary Figure S2). Respondents from Spanish-flagged vessels were more likely than those from the Ecuadorian-flagged vessels to report knowledge of a Mobulid during brailing ($p < 0.001$). When grouping respondents by role, fisheries observers were more likely than other participants to report knowing that Mobulids were present both before and during brailing ($p < 0.01$), and both observers and managerial crew were more likely than deck crew to report knowing that Mobulids were present before and during brailing (Supplementary Figure S2, $p < 0.01$). The only questions for which demographic groups did not significantly impact the differences between paired answers were for occupational role before setting, and vessel flag during brailing (Kruskal–Wallis rank-sum test; Supplementary Figure S2).

Mobulid release

Respondents reported most frequently that they used a stretcher (33.3%, $n = 72$; Figures 4b and 5a), to release Mobulids from the vessel, followed by manual release (28.7%, $n = 62$; Figures 4a and 5a). Less frequently reported release methods were using a modified brail net (10.6%, $n = 23$; Figures 4d, Figure 5a), a cargo net (9.7%, $n = 21$; Figures 4c and 5a), and an unmodified (e.g. original) brail net (9.3%, $n = 20$), followed by "other" (8.3%, $n = 18$).

The most common reasons participants gave to explain why releasing Mobulids is difficult were: the animals are too heavy or large (27.9%, $n = 74$), the lack of specific equipment on board to release them (20.4%, $n = 54$), and that they are difficult to handle (17.7%, $n = 47$) and to release (12.5%,

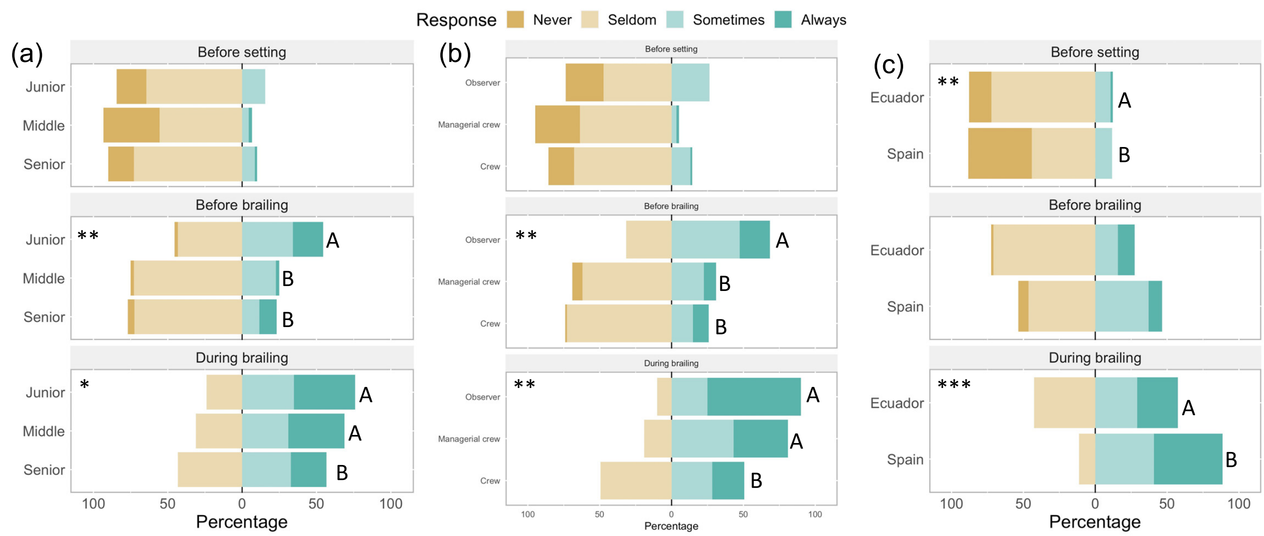

Figure 3. Survey responses of Mobulid observation before setting, before brailing, and during brailing, when netted tuna are loaded onto the vessel deck. Illustrations by Julie Johnson of Life Science Studios.

Figure 4. Commonly reported handling methods for Mobulids in the tuna purse seine fishery include (a) manual release, (b) stretcher, (c) cargo net, and (d) a modified brailer. Photos courtesy of TUNACONS.

$n = 33$; Figure 5b). Less frequently cited reasons included danger to crew (7.5%, $n = 20$), increased brailing time (6.4%, $n = 17$) and handling time (3.4%, $n = 9$), and damage to fishing gear (0.4%, $n = 1$).

When asked whether observers deploying tags to measure post-release survival of Mobulids causes a problem on board, 86.5% ($N = 147$) of respondents said there was no problem caused, while 7.6% ($N = 13$) of respondents said that it does cause a problem (10 of whom were crew members). When asked whether they were aware of prohibited handling techniques like use of gaff hooks, 73% ($N = 124$) of respondents confirmed that they were aware, while 5% ($N = 8$) said they were not aware of the prohibitions (six crew and two captains). A total of 38 respondents did not provide an answer to this question, more than any other question.

Bycatch mitigation ideas

Respondents offered novel ideas for potential bycatch mitigation methods (Figure 6). The majority of mitigation ideas focused on post-capture mortality mitigation, including using modified but existing equipment like sorting grids, modified brail nets, "sarria" nets, which are used to unload fish, and

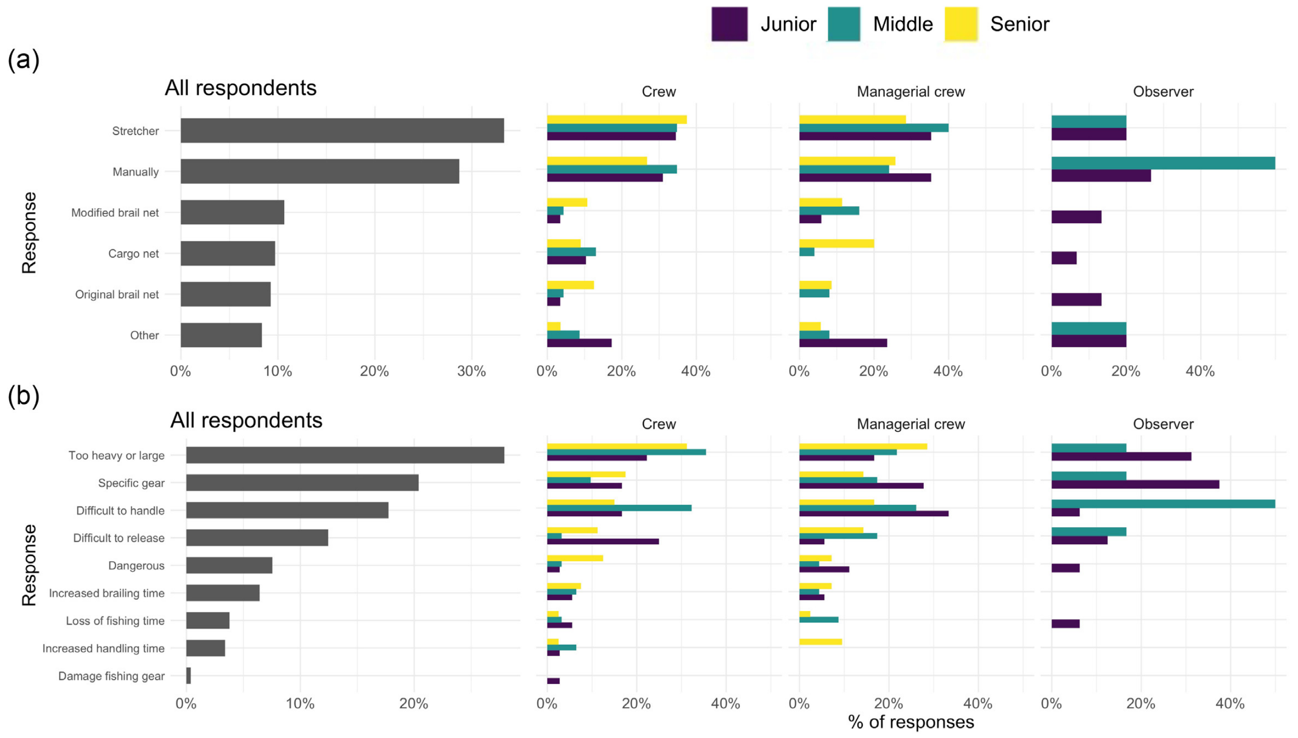

Figure 5. (a) Primary methods of Mobulid release from tuna purse seine vessels, as reported by survey respondents. (b) Reasons cited by tuna purse seine stakeholders for why Mobulids are difficult to release.

modified hoppers (a sorting bin on the deck shaped like a chute used to guide the catch). However, several responses indicated interest in avoiding areas where Mobulids are likely to be found, so that their capture may be prevented. Other novel ideas included using drones to identify and avoid Mobulids before the set, sinking the corklines (the edge of the net lined with buoys) to release Mobulids from the seine net before bringing them on board [similar to the "backdown manoeuvre" used to release dolphins (Hall *et al.*, 2017)], and using divers to release the animals from the net (Figure 6).

Focus groups

A total of 130 attendees participated in the focus groups (Table 5). The most well-represented group was fishing crew (70%) followed by managerial crew (19%; Table 2).

General information about Mobulid bycatch

Participants reported that Mobulid bycatch was relatively rare in space and time, and many noted that Mobulids are more frequently caught in "free" sets (e.g. not associated with FADs or dolphins). Some participants noted that Mobulids are caught in higher numbers off the coasts of the Galapagos Islands (July–August) and Peru (January–March). Regarding perceived changes in Mobulid bycatch, some participants said that the rate of capture fluctuates annually but is not generally different from past years. However, some participants reported perceived decreases in the rate of Mobulid capture.

Obstacles to mitigating Mobulid bycatch

Respondents expressed that a major challenge in addressing Mobulid bycatch is that they are difficult to sight in the water before capture, and that they are often only seen in the net after the set is made or during brailing. Many participants reported that large individuals are the most difficult to quickly remove from the vessel because they cannot be manually picked up by crew members. In some cases, they noted that a large animal died on deck before the crew was able to release it, as it was not able to be physically lifted by crew members and required the use of other gear. In particular for these larger individuals, respondents noted that some vessels can use a crane or hydraulic winch to remove large individuals, but that not all vessels (particularly smaller vessels) have this device.

Education and awareness

Participants indicated that they were generally aware of and in support of conservation goals for Mobulids. Some participants indicated that they did not receive sufficient information about species identification and best practices to reduce bycatch of Mobulids in relation to other bycatch megafauna species. Several indicated interest in receiving training about species identification and new technologies for mitigation. They also indicated that the most effective method of communication about Mobulids and best practices to reduce their bycatch was via visual communication.

Current and proposed bycatch mitigation methods

Several participants noted that it is common for fishing crews to pause processing tuna to release a Mobulid if indicated by the captain. Participants also mentioned a particularly promising mitigation method implemented by one vessel in the Ecuadorian-flagged fleet, which consisted of a grid of ropes on the mouth of the brailer that could filter large animals apart from the tunas and facilitate their release before they reached the deck (Figure 4d). However, the design was not widely adopted because some thought it could damage the

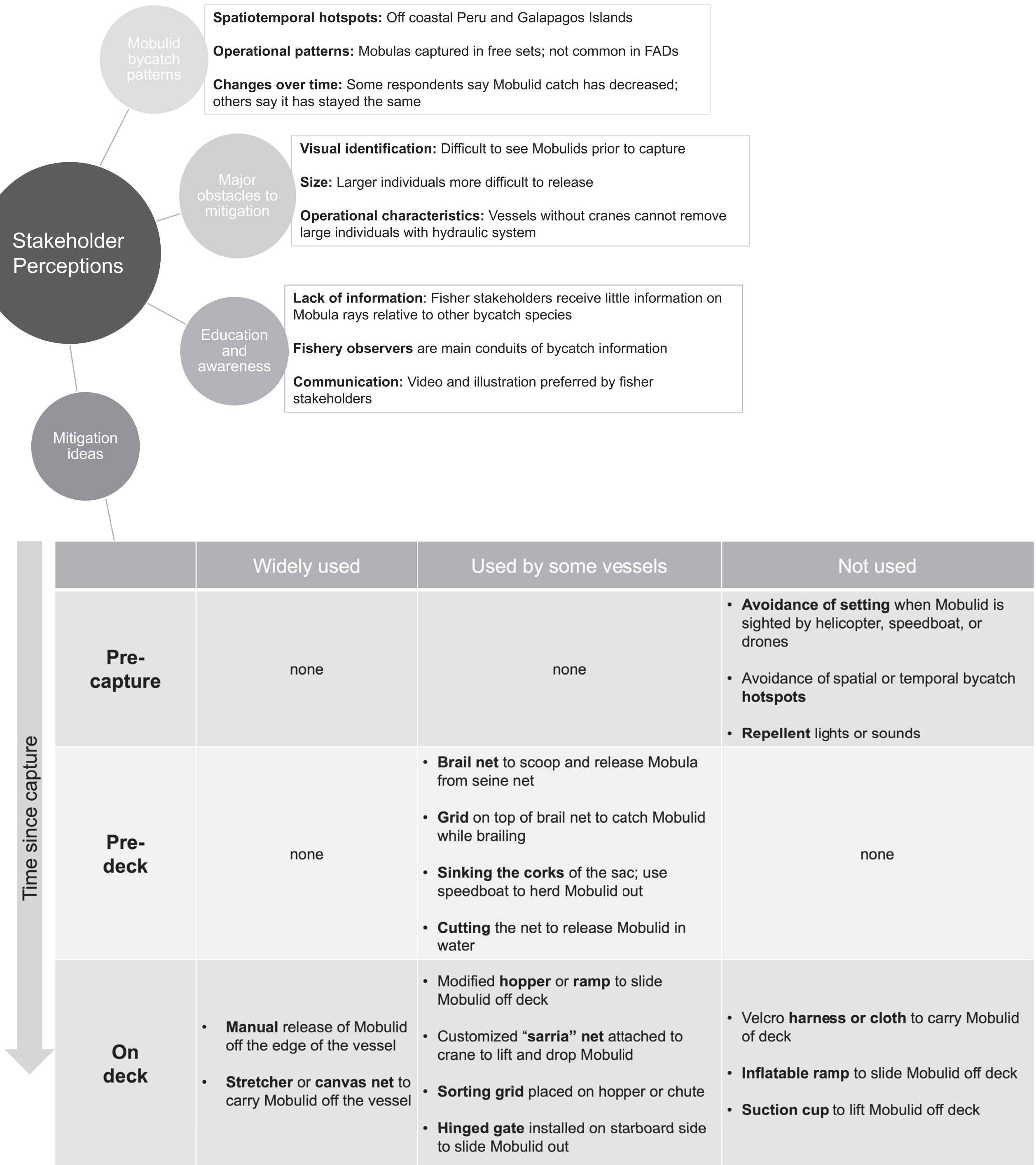

Figure 6. Conceptual summary of stakeholder perceptions of Mobulid bycatch reported by participant survey and focus group responses.

Table 5. Demographics of fishery stakeholders who anticipated in focus groups for this study.

Position	Focus group #1 ($N = 41$)	Focus group #3 ($N = 38$)	Focus group #3 ($N = 51$)	Overall ($N = 130$)
Fishing crew	31 (75.6%)	28 (73.7%)	32 (62.7%)	91 (70%)
Managerial crew	10 (24.4%)	4 (10.5%)	11 (21.6%)	25 (19.2%)
Observer	0	6 (15.8%)	8 (15.7%)	14 (10.8%)

tuna. Other mitigation ideas offered by observers were similar to those reported by survey respondents (Figure 6).

Discussion

Evaluation of the collaborative approach

The collaborative approach utilized here allowed for the collection and synthesis of quantitative and qualitative information regarding the timing of Mobulid bycatch, the state of current handling methods, and ideas for mitigation to inform the participatory development of bycatch mitigation technology in large-scale tuna fisheries. Our findings demonstrate that fishers and stakeholders have wide-ranging ideas for mitigation, and that their knowledge in some cases is influenced by their experience, role, and the flag of the vessel in which they are working. In particular, this work shows that in some cases, more junior participants observe and report more Mobulid interactions with purse seines and, hence, bycatch, before and during brailing. This finding may suggest that years at sea is not always a good indicator of participant knowledge of bycatch in this case. Our results also demonstrate that more experienced observers may be more aware of Mobulid bycatch earlier than other groups and, interestingly, that managerial crew (e.g. captains, fishing masters, and officials) report seeing Mobulids earlier in the fishing operation in comparison to deck crew. This may be a reflection of these groups having a broader view of the fishing operation on the bridge in comparison to, for instance, a fisher who is focused on processing tuna on the deck. Further, it is likely that a person's occupation and experience influence their physical position on the vessel, which then influences their likelihood of observing a Mobulid. For example, captains and officers are more likely to be surveying the sea from the vessel deck or the crow's nest—rather than focused on tasks on the deck—and, thus more likely to see a Mobulid prior to capture. Still, the fact that managerial crew may identify Mobulids earlier is promising, as, generally, only managerial crew can request to stop fishing operations so that Mobulids could be quickly released. However, deck crew who receive and physically handle Mobulids on the vessel deck may have more knowledge of potential obstacles and solutions to releasing them. This illustrates the importance of soliciting the perspectives of different members of the crew, as each role on a fishing vessel has specific knowledge of the operation and, thus opportunities for bycatch mitigation interventions.

A noteworthy constraint of the participatory approach used in this study was limited access to fishers, many of whom spend long stretches at sea out of reach. Thus, our in-person focus groups were held opportunistically during one of the two annual fishing closures for tuna purse seiners in the EPO, and due to the COVID-19 pandemic and logistical constraints, were larger in participant number and shorter in duration than is ideal for focus groups (Krueger and Casey, 2014). For this reason, we were unable to collect robust data on inter-group power and/or social dynamics that may influence participants' willingness to answer questions posed by the facilitator (Airaud *et al.*, 2020). Similarly, we did not have the opportunity to plan for directed sampling of the different fleet segments in the EPO (i.e. vessels mainly focused on free or dolphin sets, and so on) and, thus fishers that participated in our study did not reflect the full operational or geographic spectrum of tuna fishing in the EPO. This is of particular importance as observer data show that Mobulid bycatch rates are higher in free school and dolphin sets than FAD sets, and other Mobulid bycatch hotspot areas other than the ones reported by participants have been identified (Lezama *et al.*, 2019). Nevertheless, our findings are supported by similar comments and concerns that have been gathered from fishers in other oceans during workshops with fishermen (Murua *et al.*, 2014, 2019, 2020; Restrepo *et al.*, 2017).

Improvements to this participatory approach would allow for a more comprehensive understanding of the topic. For example, further research should seek to hold smaller, longer focus groups where complex topics can be fully addressed, and where researchers can observe the interpersonal dynamics among participants. This would allow for more in-depth discussion of Mobulid behavior prior to and during capture, as well as fisher input on the development of technical mitigation methods for Mobulids. Recently, Lennert-Cody *et al.* (2018) demonstrated that different segments of these fleets display differential spatial and temporal fishing strategies in the EPO. Expanding this study to identify operational characteristics associated with higher Mobulid bycatch rates would help prioritize mitigation efforts.

It is also important to target experts among fishers, as not all fishers are equally knowledgeable or equally willing to share information about all topics. Using a snowball approach, whereby existing study participants recruit future participants, further research could target highly knowledgeable participants for smaller focus groups that strategically include participants with deep knowledge of a specific step in the fishing operation (e.g. participants who decide where to fish and when to set the net). Interviewing recently retired, highly experienced fishers could help gather knowledge about changes over time in the presence of Mobulids in various fishing areas, rates of bycatch, and mitigation measures. Finally, we asked one question regarding prohibited handling practices which many fishers (22%) elected not to answer, likely due to the leading and sensitive nature of the question.

Fisher involvement in the development of mitigation methods can help define the approaches most likely to succeed, prevent wasting research resources, and increase buy-in and potential implementation by fishers. Furthermore, collaborative development of novel selective gear and protocols for Mobulids would help legitimize these mitigation efforts and spur the participation of fishers in tuna fishery management, facilitating the implementation of bycatch mitigation measures, both voluntarily by fisheries improvement projects (Grande *et al.*, 2019a) and at tRFMOs (Cvitanovic and Hobday, 2018).

Main findings

Timing of bycatch during fishing operations

A major barrier preventing the implementation of many bycatch mitigation strategies is a lack of clarity about when fishers know that non-target species have been captured. Our survey results show that fishers are most likely to first be aware of Mobulids during the brailing process, suggesting that bycatch mitigation could be most effective during this stage. However, our results also suggest that some fishers are sometimes or always aware of Mobulid presence earlier, before brailing (39%). The fact that some fishers report observing Mobulids earlier suggests that mitigation efforts should not *only* focus on release methods after brailing from the vessel deck; thus, we propose a two-pronged approach to bycatch mitigation:

(1) the development of protocols to release Mobulids from the net before brailing; and (2) the development of onboard handling modifications during brailing to reduce post-release mortality. Finally, the fact that a small proportion of respondents (12%) report that they identify Mobulids before setting the net suggests that factors that influence pre-capture detection is a priority for further research.

Major challenges and potential solutions

Overall, stakeholders reported concern over Mobulid bycatch and interest in supporting mitigation for their conservation. However, the major obstacles identified by participants—namely, the difficulty in seeing Mobulids before capture, the difficulty of releasing large individuals safely and the lack of specific equipment to do so, and the relative rarity of their capture—provide potential opportunities to target mitigation and management interventions. The reported difficulty of releasing large individuals is significant, as medium and large individuals (> 90–150 cm, > 150 cm of disc width) comprise the overwhelming majority (∼85%) of Mobulid bycatch in the EPO purse seine fishery, at least in most recent years (IATTC, unpublished data). For these first two obstacles, we suggest that minimal changes in operational procedure could help ameliorate their impacts. To address the lack of specific devices to handle and release large individuals, properly designed brailer grids and tools for releasing Mobulids could aid in quick release of even the largest individuals, and could be tailored for vessels with and without hydraulic gear (e.g. winches and cranes). These modifications are potentially low-cost and, according to our results, would be supported by stakeholders in the fishery, but would also contribute to the recommendation of reducing post-release mortality suggested by the ecological risk assessment for *M. mobular* in the EPO (Griffiths and Lezama-Ochoa *et al.*, 2021). Several prototypes, including brailer grids and hinged swinging doors installed the side of the vessel deck, are being tested across oceans for rapid and non-intrusive releases (IATTC-TUNACONS, 2019; Murua *et al.*, 2019, 2021; Santiago *et al.*, 2019; Mandelman *et al.*, 2022). These efforts should be accompanied by investigation of potentially detrimental impacts of these devices on Mobulids' survival through, for example, tagging experiments to investigate post-release survivorship. Additionally, future studies should explore the multiple impacts of the technical mitigation methods on the tuna quality to address concerns about damage to tuna that were expressed by stakeholders in this study.

Education and awareness

This research identified several informational and educational gaps that, if addressed, would help inform and incentivize Mobulid bycatch mitigation in tuna purse seine fisheries. In particular, some focus group participants noted that they do not receive as much information about Mobulids as they do for other bycatch species. Educational materials, particularly those that promote visual communication such as posters or digital apps, as well as regular training that communicate biological details of Mobulids and the regulations in force in their region, are crucial to ensure reliable data collection and inform fishers about mitigation policies. Particularly for Mobulids, which can appear morphologically similar and for which accurate species identification in purse seine fisheries may be low (Lezama-Ochoa *et al.*, 2019). This is important, as preliminary evidence suggests post-release mortality rates may vary for Mobulid species, and thus evaluations of the bycatch mitigation strategies proposed here will need to consider intraspecific variability in survival (Francis, 2014; Restrepo *et al.*, 2018; Hutchinson *et al.*, 2021). Training in species identification and easy-to-use identification guides and apps could help support and empower fishers to accurately identify and release Mobulids and build capacity. For example, our team produced and distributed educational posters and translated these into appropriate major languages (e.g. Spanish, Taiwanese, Korean for the EPO; Bahasa, Mandarin, Tagalog, Spanish, and Taiwanese for the Western Pacific and Indian oceans; English, Spanish, and French for the Atlantic) for tuna fishers in each ocean (https://www.mobulaconservation.com/industrial-fisheries/). The dissemination of creative visual materials can help communicate the mitigation methods informed by this study.

Evaluation of current global conservation measures

Based on the results of this study, we attempt to address the feasibility of some measures currently in place, identify priority topics for scientific research related to these, and propose improvements to existing measures and recommendations.

Prohibiting intentional setting on tunas associated with Mobulids

Currently, two tuna management organizations—IOTC and WCPFC—have bans on intentionally setting on Mobulids (Table 1). However, in order to avoid setting on tunas that swim in association with Mobulids, it would be necessary to detect or predict the presence of Mobulids before the net is set. This study suggests that no matter the level of experience of the fishers at sea, their role in the fishing vessel or flag, most fishers never or seldom detect a Mobulid before the net is set (Figure 2). Still, the fact that a small proportion of respondents (12%) report that they can do so—and that most of those respondents (70%) use visual identification to do so—suggests that further research should investigate tools and protocols that could allow fishers to visually identify Mobulids. Particularly for occasions when large aggregations of Mobulids are encountered, leading to high bycatch in a single set, these interventions could avoid interactions before setting the net (Lezama-Ochoa *et al.*, 2019). These avoidance actions are likely to have the most benefit for Mobulid survival, as they would avoid the stress associated with confinement in the net and injury during the brailing process. For instance, fishers regularly use sonar and binoculars, sometimes from the crow's nest, when they approach a tuna school to identify the species and size of the tuna (Moreno *et al.*, 2007). Ecological research on Mobulids has demonstrated that they are easily visible and identifiable by plane and aerial drone survey, at least when they are at the water's surface (Notarbartolo and Hillyer, 1989; Pate and Marshall, 2020). Interviewing helicopter pilots, two of whom in our survey reported that they are "sometimes" aware of Mobulids before setting, could be a valuable next step to identify factors that would improve or automate detection and avoidance of Mobulids before setting.

Beyond visual identification, fishers have, over many years spent at sea, maximized their ability to detect and assess tuna schools, an expertise that could be harnessed to develop protocols and technologies for bycatch avoidance. A recent topic of research on the tuna purse seine fishery is the acoustic discrimination of tuna species (Moreno *et al.*, 2019). Although acoustic equipment is widely used by fishers to detect and evaluate the amount of tuna in every set, no studies have investigated the utility of acoustic detection of Mobulids using existing equipment onboard purse seiners. Further research could investigate the applicability of these technologies for avoidance of Mobulids, sharks, and other bycatch species. Similarly, the development of species distribution models for tuna and Mobulid species within the framework of a dynamic ocean management could provide significant insight on where and when vessels could avoid interaction with the species while maintaining catches of target species. First steps for this process have already been undertaken in the EPO (Lezama-Ochoa *et al.*, 2019; Lopez *et al.*, 2019), but there is still no management guidance on how to use such a tool practically.

Nevertheless, even if adequate technologies were developed to detect Mobulids, it remains unclear whether fishers would intentionally avoid a Mobulid associated with a tuna school, given the lack of incentives to do so currently (Tolotti *et al.*, 2015). As a short-term solution, observers or other officials trained to anticipate and record bycatch species could be tasked to detect Mobulids; though there is little precedent for such a position currently. For these reasons, we conclude that the effectiveness of a potential conservation measure that bans intentional setting on tunas in association with Mobulids may currently be low given lack of adequate capability to detect them and insufficient incentives, and thus should be combined with other mitigation actions. In the longer term, implementing avoidance of Mobulids (and other bycatch species) would require increased engagement between scientists, managers, and fishers to produce a comprehensive plan to set up social and economic incentives (e.g. norms, price premiums, and certifications) and disincentives (e.g. quotas, levies, and sanctions) for bycatch avoidance (Pascoe *et al.*, 2010).

Handling and release practices

Currently, conservation measures in all tRFMOs except one require vessels to release Mobulids alive and unharmed in a manner that results in the least possible harm to the Mobulids (Table 1). This is an improvement from the past, when harmful onboard handling practices may have resulted in high levels of post-release mortality for this group (Hall and Roman, 2013). However, these conservation measures apply only after the Mobulid arrives on the purse seiner's deck, and do not address the risks associated with concentration in the sack, a highly restricted area where the density of fish prevents swimming and where dissolved oxygen levels may drop quickly. Therefore, from the perspective of maximizing survivorship and given Mobulids' reliance on ram ventilation (a type of respiration that requires constant flow of water over the gills), the sooner the release takes place within the fishing operation, the higher the survival probability. Currently, there are no specific best handling practices to release Mobulids from the net before sacking, mainly due to the lack of research focused on this issue.

In the past, trials to release non-target species directly from the net, such as cutting a top panel of the net to create an escape opening (Itano *et al.*, 2012; Hutchinson *et al.*, 2019) or lowering the corklines to allow them to swim out (Grande *et al.*, 2019b, Escalle *et al.*, 2016), have been tested on purse seine vessels for non-target species. Some of the lessons learnt, particularly from trials with other elasmobranchs, could also inform mitigation efforts for Mobulids (Hutchinson *et al.*, 2015). For example, trials of escape panels for sharks have identified various technical and behavioral issues which may also be relevant for Mobulids (Restrepo *et al.*, 2018). One problem was that the sharks did not receive cues to exit through the panel, an issue that could affect Mobulids as well. To test the feasibility of escape panels for Mobulids, better understanding of their behavior and Mobulid–tuna spatial segregation in the net before and during sacking is necessary. This would allow for the identification of the best timing and placement to release Mobulids from the net. The use of divers to direct Mobulids out of the net could be a potential solution, although fishers in our focus groups were divided on whether this would be a practical solution or a dangerous one. Fishers in this study also mentioned that the release of Mobulids could be done from the net by sinking the cork line, similar to the backdown manoeuvre made to release dolphins from the net on by purse seiners that target tunas associated with dolphins (Jenkins, 2007). This manoeuvre could be tested for its efficacy for the release of Mobulids; however, it would only apply to those vessels catching tuna associated with dolphins, as using the backdown manoeuvre in other types of vessels is believed to be risky and not effective for avoiding other vulnerable bycatch species.

Novel ideas by fishers

Apart from the research mentioned in the previous sections that may improve current conservation measures, participants proposed new ideas to avoid and mitigate bycatch (Figure 4). Some of the ideas produced by participants in this study, including the use of drones, repellents, and other novel technologies, have not yet been widely used or explored, and would require significant research efforts to test their feasibility and effectiveness in commercial fishing operations. However, other proposed methods, such as modified brail nets, hinged doors in vessel sides, and cutting seine nets, have been used at least on some tuna purse seine fishing vessels in these fleets, and appear to be feasible for use in other settings. Many of the mitigation measures proposed were relatively simple and involved the use of materials already currently on board a typical tuna purse seine vessel (e.g. cargo nets and tarpaulins). Further research should investigate the potential for fishers' suggested methods to reduce post-release mortality of Mobulids and their impacts on tuna catches and quality. For example, the sorting grids currently being tested to release Mobulids on some purse seiners were initially suggested by fishers in workshops, and then developed later by scientists and engineers (Murua *et al.*, 2020).

Conclusion

The results of this study improve our understanding of the operational and fine-scale temporal circumstances of Mobulid capture, and can aid in the collaborative development of bycatch mitigation strategies for Mobulids. However, most if not all of the approaches we report in this study have not been rigorously evaluated for their potentially efficacy in reducing Mobulid mortality. Broadly we suggest that future research and regulatory efforts should focus on three promising directions: (1) pre-capture mitigation strategies (e.g. avoidance of hotspots using static or dynamic spatial-temporal management), (2) post-capture mitigation strategies (e.g. best handling practices and release technologies); and (3) the evaluation of the impacts of these methods on (i) species-specific bycatch survival rates, and (ii) target species yield using these methods. The fact that respondents noted that some vessels are already piloting *ad hoc* mitigation methods that include these is promising. Before these methods can be scaled, research and funding efforts should prioritize testing promising solutions, like those we identify in this paper (e.g. brailer grids, fleet communication with helicopter pilots, acoustic detection, and so on). Most importantly given their sensitive physiology, these efforts should strive to focus on pre-capture bycatch avoidance methods, which have high potential to reduce a primary threat for threatened Mobulid rays.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Data availability

The data underlying this article cannot be shared publicly to protect the privacy of individuals that participated in the study. The data will be shared on reasonable request to the corresponding author.

Author contributions

MRC, DC, and GM conceptualized the study. MRC, GM, MAH, DC, JDS, NLO, and JL designed and refined the survey instrument. MRC, NLO, and SR collected the data. MRC, JLW, and GM conducted the analysis. MRC, GM, MAH, DAC, JDS, NLO, VR, JL, JM, JLW, HM, and SR contributed to the writing and revision of the manuscript.

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