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Technical mitigation measures for sharks and rays in fisheries for tuna and tuna-like species: turning possibility into reality

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Abstract – Tuna fisheries have been identified as one of the major threats to populations of other marine vertebrates, including sea turtles, sharks, seabirds and marine mammals. The development of technical mitigation measures (MM) in fisheries is part of the code of conduct for responsible fisheries. An in-depth analysis of the available literature regarding bycatch mitigation in tuna fisheries with special reference to elasmobranchs was undertaken. Studies highlighting promising MMs were reviewed for four tuna fisheries (longline, purse seine, driftnets and gillnet, and rod and line – including recreational fisheries). The advantages and disadvantages of different MMs are discussed and assessed based on current scientific knowledge. Current management measures for sharks and rays in tuna Regional Fishery Management Organizations (t-RFMOs) are presented. A review of relevant studies examining at-vessel and postrelease mortality of elasmobranch bycatch is provided. This review aims to help fisheries managers identify pragmatic solutions to reduce mortality on pelagic elasmobranchs (and other higher vertebrates) whilst minimizing impacts on catches of target tuna species. Recent research efforts have identified several effective MMs that, if endorsed by t-RFMOs, could reduce elasmobranchs mortality rate in international tropical purse seine tuna fisheries. In the case of longline fisheries, the number of operational effective MMs is very limited. Fisheries deploying driftnets in pelagic ecosystems are suspected to have a high elasmobranchs bycatch and their discard survival is uncertain, but no effective MMs have been field validated for these fisheries. The precautionary bans of such gear by the EU and by some t-RFMOs seem therefore appropriate. Recreational tuna fisheries should be accompanied by science-based support to reduce potential negative impacts on shark populations. Priorities for research and management are identified and discussed.

Keywords: Mitigation / elasmobranch / bycatch / pelagic / mortality / tuna regional fishery management organizations

1 Introduction

Global fishing effort was roughly constant from 1950 to 1970, but increased steadily in subsequent decades (Anticamara et al. 2011). In 2005, global discards were estimated at 6.8 million tonnes (mt) for 78.4 mt total reported landings: a global discard rate of 8% (Kelleher 2005). Tuna and tuna-like species are of great importance as a global food resource and are of major economic value. Their reported global landings have increased continuously from <0.6 mt in 1950 to 7 mt in 2010 (FAO 2014). Bycatch in tuna fisheries is the primary source of fishing mortality of some marine species (Bellido et al. 2011), and tuna fisheries have been identified as one of the major threats to populations of various marine vertebrates, including marine turtles (Lewison et al. 2004; Baez et al. 2013; Roe et al. 2014), sharks (Gilman et al. 2007; Huang 2011), seabirds (Croxall et al. 2012; Lewison et al. 2012) and marine mammals (Forney et al. 2011; Macías et al. 2012).

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Fisheries for tuna and tuna-like species operating around the world are managed under the auspices of various tuna Regional Fishery Management Organizations (hereafter referred to as t-RFMOs). Historically, t-RFMOs did not address bycatch issues, and only limited management actions were introduced. In recent years, however, t-RFMOs have included bycatch issues in their mandate and established working groups on bycatch and ecosystems to better address bycatch (Gilman et al. 2014). Options for technical mitigation measures (MMs) and bycatch reduction research have been central to these discussions, with several novel initiatives developed and many on-going studies (e.g., Kelleher 2005; Soykan et al. 2008; Gilman 2011). Some of these initiatives have been developed against a background of increased global efforts by environmental non-governmental organizations (ENGOs) to encourage innovative MMs (e.g., Bazilchuk 2005).

The development of MMs in fisheries as a part of responsible fisheries was first introduced in the 1982 Law of the Sea Convention (United Nations 1982), and addressed further in the subsequent Code of Conduct for Responsible Fisheries (FAO 1995). Various national and international projects have investigated potential MMs to reduce negative impacts of tuna fisheries on bycatch taxa, which have helped t-RFMOs adopting bycatch reduction management measures to either protect particular taxa of conservation concern or to regulate a particular fishery.

Information on MMs has been collated in a variety of initiatives. The Western and Central Pacific Fisheries Commission (WCPFC) maintains the "Bycatch Mitigation Information System" (BMIS), a database that provides the latest information on the mitigation and management of incidental bycatch taken by fisheries targeting highly migratory species (http://www.wcpfc.int/bmis; accessed October 2015). This information is also of relevance to similar oceanic fisheries elsewhere in the world. The development of the BMIS was part of joint t-RFMO efforts that were facilitated under the Kobe III process (Fitzsimmons and Bunce 2013). Similarly, the New England Aquarium maintains a database of references and summaries from bycatch reduction studies, as well as descriptions of bycatch MMs (Consortium for Wildlife Bycatch Reduction's website: http://www.bycatch.org; accessed October 2015) and the International Sea Food Foundation (ISSF) maintains a website with an index to t-RFMO measures (http://iss-foundation.org/rfmo-resolution-database; accessed October 2015). These initiatives list and describe recent developments addressing bycatch issues, which can be shared with fisheries managers, scientists, fishers and the public.

Whilst initial research on MMs focused on "charismatic megafauna" (marine mammals, sea turtles and seabirds), elasmobranchs (sharks and rays) have become of increased scientific, public and political concern since the 1990s. However, there are differences in the efficiency between MMs suggested to reduce impacts on elasmobranchs, which in some cases have been adopted by some countries and/or fishing entities.

Several reviews of mitigations measures in tuna longline and purse seine fisheries have been published (Gilman 2011; Clarke et al. 2014; Hall and Roman 2013). A meta-analysis of published studies indicated the potential effectiveness of some MMs in longline fisheries (Favaro and Côté 2015). However, none of them includes a qualitative ranking system to assess the performance of the MMs. Here, a comprehensive review of existing MMs for several fisheries and a qualitative assessment of their success in terms of reducing bycatch (or dead discards) of elasmobranchs is provided, with their advantages and disadvantages assessed using defined criteria. This study takes a global view and the potential impacts of MMs on target species, other bycatch groups and the environment are considered as well as current management measures for sharks and rays in t-RFMOs. For effective management measures to be implemented, it is crucial to have appropriate estimates of both at-vessel and postrelease survival rates for relevant species, as this determines the efficacy of MMs (Carruthers et al. 2009). Therefore, an in-depth analysis of the current bycatch mitigation and management literature, as well as discard survival studies was undertaken, with recent innovations highlighted and important data gaps identified.

2 Material and methods

2.1 Fisheries

Four main fisheries for tuna and tuna-like species were considered; (1) longline fisheries (surface and deep-sets), (2) purse seine fisheries, (3) driftnets/gillnets, and (4) rod and line fisheries (typically recreational).

2.2 Web sites and literature reviews

The websites of the five main t-RFMOs (Inter-American Tropical Tuna Commission (IATTC), International Commission for the Conservation of Atlantic Tunas (ICCAT), Indian Ocean Tuna Commission (IOTC), Western and Central Pacific Fisheries Commission (WCPFC), and the Commission for the Conservation of Southern Bluefin Tuna (CCSBT) were consulted to summarize all relevant recommendations and resolutions that have been adopted for elasmobranch conservation and management.

Advantages and disadvantages of generic MMs (suitable for all fishing gears) were then identified from the literature. Published literature on elasmobranch bycatch and MMs for fisheries targeting tuna, tuna-like species and/or sharks was reviewed for the four gear groups. Literature sources were identified by searching Bycatch Mitigation Information System (BMIS), ISI Web of Knowledge, the data base of the Consortium for Wildlife Bycatch Reduction and working documents submitted to relevant t-RFMO working groups.

Publications examining at-vessel ("at-haul back" or "hooking") and postrelease survival were identified based on library and electronic database searches using relevant key words (mortality, survival, survivorship and shark, ray and elasmobranch) and covered the period 1992 to March 2015. The review focused on studies relating to elasmobranchs taken in fisheries targeting tuna, tuna-like species and/or sharks. For each study, the following information was collated: (1) study location and origin of the data; (2) objectives of the study;

(3) gear type; (4) results for at-vessel and overall survival by species; (5) estimates of postrelease survival; (6) MMs proposed and management implications; and (7) the main results of the study (see Table S1).

2.3 Performance assessment of technical mitigation measures

After identifying potential types of interactions with fishing gears, and a short description of each mitigation option, detailed comments on the advantages, disadvantages and caveats for each MM are provided. Technical MMs were categorized as "fishing gear modification", "fishing practices and strategy", and "Protocols to increase survival rates after release". The performance of potential MMs found in the literature was assessed against 14 criteria (nine derived from Patterson and Tudman 2009) and five additional criteria). Seven of the criteria assessed the biological and environmental impact of the MMs and addressed the following questions (Patterson and Tudman 2009):

(1) Could the mitigation measure reduce interactions with elasmoranchs?
(2) Could it minimize the level of discarding?
(3) Could it facilitate the escape of by-caught individuals?
(4) Could it improve the survival of elasmobranchs?
(5) Could other higher vertebrate taxa likely derive benefit from the measure?
(6) Could it have other positive impacts on the environment (e.g. in relation to pollution or habitat degradation)?
(7) Could it affect fuel consumption and/or the carbon footprint?
The remaining group of criteria assessed the impact of the measure on the fishing activity and the perception of the measure by the fishing industry, and addressed the following:
(8) Would the measure impact overall catch, catch rates or quality of the target species?
(9) How easily could a positive response be detected?
(10) Would implementing the measure induce additional costs?
(11) How difficult would be the implementation?
(12) Would it impact current data collection on bycatch?
(13) Would it impact crew safety?
(14) Would the fishing industry be supportive?

A qualitative ranking system was adopted to synthesize all information given equal weighting to all criteria. Attribute values were derived from comments given in the publication and also from the expertise of the authors. Each criteria was scored on a 5-point scale (+2 to –2) where –2 = very negative impact on bycatch and/or an anticipated very poor acceptance from fishers, –1 = negative impact and/or poor acceptance, 0 = none or unknown effect or not applicable; 1 = positive impact and/or acceptance, and 2 = very positive impact and/or acceptance. The overall score for each MM was the sum of the scores for each criterion. It was also identified whether the measure was experimental, tested at a large scale, or already implemented in the field.

3 Current mitigation measures in fisheries of tuna and tuna-like species

3.1 Overview

Currently 35 management resolutions or recommendations for elasmobranchs have been adopted by the five main t-RFMOs to mitigate the effects of tuna fishing on elasmobranch populations. These cover sixteen types of technical MMs (Table 1). Most measures are recent, with 5 (14%) having been adopted between 2004 and 2005 and 24 (69%) since 2009 (Table 1).

The literature review identified nine generic MMs that have been recommended irrespective of the fishing gear. These measures range from input controls to limitations on what (species, sizes) can be retained on board. All generic MMs have advantages and drawbacks (Table 2).

3.2 General assessment of technical bycatch mitigation measures

The published literature on this topic has increased in recent years. Of a total of 118 relevant studies identified for the period 1963–2015, 103 (87%) have been published since 2005 (Tables 3 and 4). The literature analysis provided an indication of how the MMs may benefit elasmobranchs, other taxonomic groups and the environment, as well as how they could impact the profitability of the fishery and logistic considerations for practical implementation. The review showed, for all gears combined, that gear modifications were the most widely proposed measure (19 MMs) followed by fishing strategy (13 MMs), with three generic MMs irrespective of gear type (Table 3). The assessment scores for the three categories ranged from 0 to 12 (overall score) while overall scores for all criteria combined ranged from 1 to 20 (Table S2d). This ranking is intended to help managers identify potential management options, based on best available current knowledge.

Three mitigation measures belonging to the third category of measures ("Enforcement of safe handling and release", "Workshops and training", and "Mandatory sea turtle/shark handling tools"), as practices to increase survival rates after release in all fisheries obtained high scores (13–20), as fishers are generally supportive of these measures, they would be easy to introduce, and incur limited expenses (Table S2d).

3.3 Mitigation measures for longline fisheries

Twenty potential MMs were identified for longline fisheries, comprising 11 for "Fishing gear modification", six for "Fishing practices and strategy" and three for "Practices to increase survival rates after release". Overall scores ranged from 5-19 (Fig. 1, Table S2da). Among the MMs in the "Fishing gear modification" category, "Prohibition of wire leaders" obtained the higher scores for both tuna and swordfish longline fisheries (score = 19) and "Prohibition of light attractors" for tuna fisheries (score = 16). Use of "Artificial bait" was identified as potentially useful to improve selectivity, but further development is needed (score = 17). The MMs

Table 1. Summary of the main resolutions (Res.xxx), recommendations (Rec.xxx) and conservation and management measures (CMMxxx) specifying management measures relating to elasmobranchs implemented by t-RFMOs during the period 2003 to 2014. IATTC: resolution binding, recommendations non-binding; ICCAT: recommendation binding, resolution non-binding; WCPFC: Conservation and management measure binding, resolution non-binding; IOTC: resolution binding, recommendation non-binding; CCSBT: recommends to members and cooperating non members to comply with all current binding and recommendatory measures aimed at the protection of ecologically-related species (including elasmobranchs) adopted by IOTC, ICCAT and WCPFC.

Management measure	IATTC	ICCAT	IOTC	WCPFC
Implementation of shark NPOA		Res 03-10		
Prohibition of wire for tuna-directed fisheries				CMM 2014-05
Report catch	Res.C05-03	Res.04-10	Res.05-05	CMM2010-07
Full utilization of shark products	Res.C05-03	Res.04-10	Res.05-05	CMM2010-07
5% fins/body ratio	Res.C05-03	Res.04-10	Res.05-05	CMM2010-07
Mitigation research	Res.C05-03	Res.04-10	Res.05-05	Res.2005-03
Reporting in logbooks	Res.C05-03	Rec.07-06	Res.10-02 /13-03	Res.2005-03
Observers	Res.C11-08	Rec.11-10	Res.11-04	CMM 07-01
				CMM2014-01
Prohibition of retention of:				
– Thresher sharks *Alopias spp.*		Rec.09-07 [1]	Res.12-09 [2]	
– Oceanic whitetip shark *Carcharhinus longimanus*	Res.C11-10 [3]	Rec.10-07 [4]	Res.13-06 [5]	CMM2011-04 [6]
– Hammerhead sharks *Sphyrna spp.,*		Rec.10-08 [7]		
– Silky sharks *Carcharhinus falciformis*		Rec.11-08 [8]		CMM2013-08 [9]
Prohibition of purse seine setting on whale sharks	Res.C13-04			CMM2012-04
Prohibition of large scale driftnets in the high seas		Rec.03-04	Res.12-12	CMM2008-04
Management plans for sharks fisheries				CMM2014-05
Encourage the release of live sharks, especially juveniles		Res.01-11/Rec.15-06		
Estimates of the mortality of non-target species (all sharks)				CMM2004-04
Encourage research on shortfin mako	Res.C15-04	Rec.14-06		
Conservation of Mobulid rays caught in association with fisheries				

CCSBT: With only one exception, all CCSBT members and cooperating non-members are also parties or cooperating parties to IOTC, WCPFC and/or ICCAT. As a consequence, any binding bycatch mitigation measure of these RFMOs is in practice binding for the CCSBT member/cooperating non-member when fishing within that convention area.

NPOA: National Plan of Action.

influencing hook characteristics (“Corrodible hooks”, “Weak hooks” and “Increased hook size”) scored 10–15. Nevertheless, the additional time needed to prepare the gear and the drastic changes in the fishing gear itself would likely hamper the acceptance of such measures by fishers. The use of “Circle hooks” only, i.e. prohibition of J-hooks and tuna hooks, scored 11 and, although implemented in several areas already, more detailed case studies are needed. Those MMs dealing with deterrents (“Magnetic, electropositive or electrical deterrents”; “Olfactory repellents”; “Auditory deterrents/attractors”) scored poorly at the present time, as these options have never been successfully field-tested.

Among the measures within the “Fishing practices and strategy” category, the highest ranking options were: “Deep setting”, “Fleet communication” and “Management of offal and spend discharge” (scores = 14, 14 and 12, respectively) and were considered easy to implement and at no extra cost. “Prohibiting the use of live bait” (score = 11) may also be an acceptable measure, as it would impact on few fisheries. While “Reduced soak time” (score = 10) would be less popular with fishers, especially for longliners where swordfish and sharks were important catches, as fishers assume that it would be associated with reduced catches of target species. “Restricting fishing on topographic and oceanic features” (score = 10) was considered difficult to implement, and more comprehensive studies on the temporal and spatial distribution of sharks in relation to their position in the water column and in relation to water temperatures (including oceanic fronts etc.) are necessary.

Among the 20 MMs considered, 17 (85%) were also considered beneficial for other bycatch groups, twelve (60%) might reduce interactions with sharks, 13 (62%) might have the ability to minimize the level of discarding (as opposed to facilitating escape from the gear, which was found in only four cases), and eight (38%) could improve survival. Two of the MMs might increase fuel consumption (“Reduced soak time” and “Restricting fishing on topographic and oceanic features”) and another two might reduce the impact on the wider environment, whether by reducing plastic and battery waste (“Prohibition of light attractors”) or through reduced pressure on resources of bait fish (“Artificial bait”).

[1] *Alopias superciliosus*.
[2] *Alopias spp.*
[3] *Carcharhinus longimanus*.
[4] *Carcharhinus longimanus*.
[5] *Carcharhinus longimanus*.
[6] *Carcharhinus longimanus*.
[7] *Sphyrnidae* (except for the *Sphyrna tiburo).*
[8] *Carcharhinus falciformis*
[9] *Carcharhinus falciformis*.

Table 2. Summary of advantages and disadvantages of generic management measures for reducing bycatch of elasmobranchs in tuna and tuna-like fisheries.

Management measure	Advantage	Disadvantage	Remarks	Source
Legal constraints in fishery for fin cutting and removal	• Fishing effort and fishing mortality on sharks could be reduced, as numbers retained depend on hold capacity, as fins were a high-value, low volume product • Enables better quantification and species identification of landings	• Fishers argue that the obligation of landing the shark carcass with fins naturally attached reduces on-board storage, increases labour costs and that the flesh can deteriorate when defrosting is required for removing the fins • Required high rates of observer coverage and/or inspections when vessels land • Possible increase in trans-shipment of fins if low levels of enforcement at sea	• Finning prohibitions divert attention from assessing whether catch levels are sustainable • Issues with compliance and enforcement	Camhi et al. (2008); Walsh et al. (2009); Clarke et al. (2013)
Quotas for bycatch species	• Quotas may help limit landings	• Benefit to stock in question depends on discard survival • May incentivize finning or high grading		this study
Species retention prohibition	• Reduced fishing mortality on the most vulnerable bycatch species • Depending on their levels of occurrence and/or market value, may not have severe cost to the fishing industry	• Benefit to species in question depends on discard survival • Possible identification problems with some taxa • Some "prohibited species" may have high value products (e.g. fins, gill rakers, jaws)	• Can impact on retention of dead specimens for scientific study	this study
Minimum landing size (MLS; the smallest length at which it is legal to retain the species)	• MLS regulations can encourage fishing to occur on grounds where small fish are less abundant • Fishers may improve gear selectivity to reduce capture probability of young fish	• If MLS regulations do not decrease encounter rate, then their success is dependent on small fish being released live and having a high postrelease survival	• In some species (e.g., blue shark and shortfin mako) it has been shown that at-vessel mortality is higher in smaller individuals • Studies to better delineate pupping and nursery grounds should be encouraged	Carruthers et al. (2009); Coelho et al., (2012, 2013)
Maximum landing length (MLL; the largest length at which it is legal to retain the species)	• Discourages the targeting of larger individuals, which are often mature females and the most fecund • MLL regulations can encourage fishing effort to move away from areas at times when large (often female) sharks aggregate	• Larger sharks can be higher value • Effectiveness depends on discard survival • If the species is a targeted species, then the effectiveness also depends on whether effort is redirected to smaller fishes	• Can create problems for how fishers assess the size of larger fishes, especially when alive. • In some cases, a degree of tolerance may be required by enforcers if some fish are just over MLL, especially if post-mortem changes allow landed fish to be "stretched" more easily when measuring	

Table 2. continued.

Compensation mitigation/ Industry self-policing	• Reduction of shark catches and mortality • Greater involvement of fishers in the management of their fisheries • Could enhance collaborative work with scientists to reduce bycatch and bycatch mortality	• May impact the sustainability of the activity for boats which cannot reach the goals	• Regulations proposed by authorities or by the fishing industry itself could financially penalize individual vessels or a fisheries association when bycatch standards are not met • Reducing or withholding any subsidies, or increase cost of the permit or license fee • Fisheries may benefit from 'environmental' accreditation if their main catch receives a higher value	Gilman (2011)
Spatial/temporal closure Regulations involving closure or gear restrictions in particular fishing zones and/or fishing seasons.	• Reduction of shark catches and mortality • Reduction of catches and mortality for other taxa	• Could induce an increase in fuel consumption for reaching other fishing grounds • Cause problems to fleets with limited range capacity • Could increase fishing impact on other grounds through fleet displacement • Can be difficult to enforce in high seas areas • Closed areas in remote high seas areas that affect legal fleets may then be targeted by IUU vessels	• Necessity to know the patterns of habitat use, by sex and by sizes, both horizontal and vertical of shark and other taxa • Need to understand the likely response in fleet behaviour to gauge benefits to stocks of concern in relation to potential impacts on other fishing grounds • Easy to monitor and enforce within the Exclusive Economic Zones of the regulating nation and fleets equipped with VMS • Regulation in international waters is restricted to the fisheries of the regulating nation or international agreements	Alverson et al. (1994); Leathwick et al. (2008); Dunn et al. (2011); Senko et al. (2014)
Fishing effort reduction Limits on the overall fishing capacity of the fleet	• Reduction of shark catches and mortality • Reduction of catches and mortality for other taxa	• Can have financial implications if the vessels still need to travel long distances to the fishing grounds but once there they have to reduce the effort (less hooks or sets). • Monitoring compliance can be difficult (and expensive) to achieve/implement	• Various approaches can be used to limit overall fishing effort, such as limiting the number and sizes (or capacity) of vessels participating in a fishery, the number of hooks, the number or duration of fishing operations • Reducing vessel size could reduce fuel consumption	Davis and Worm (2013)
Bycatch management	• Reduction of shark catches and mortality • Reduction of catches and mortality for other taxa	• Any measure that restricts fishing faces reluctance by the industry • Land-all policies can result in mixed fisheries being closed early when the catch limits for the species with the smallest quota are reached ("choke" species), or if bycatch limits of vulnerable taxa are exceeded	Several management approaches have been developed to reduce wastage, bycatch, and discarding in fisheries Examples include (1) national bycatch policy; (2) bycatch quotas or caps; (3) individual habitat quotas (IHQs); (4) bycatch tax system (5) zero (dead) discards policies	Davis and Worm (2013)

Table 3. Advantages and disadvantages of technical mitigation measures for reducing elasmobranch catches in tuna and tuna-like fisheries and overall score obtained by each measure. Longline fisheries (SWO: Swordfish, TUN: Tuna SHK: Shark)

Mitigation category	Mitigation measure Overall score	Advantage	Disadvantage	Remarks	Source
Fishing Gear modifications	**Prohibition of light attractors** (no chemical light sticks, battery-powered light-emitting diodes, "electrolume", etc.) SWO: **10** TUN: **16** SHK: **14**	• Reduced shark and sea turtle bycatch • Reduced pollution (plastic containers, chemical components, batteries). • Easy to implement.	• Fishers fear reduced catch rates of target species. • Fishers could increase effort (sets, number of hooks per set) to compensate perceived loss of catches.	• Already implemented in some areas • Effectiveness of the chemical light-sticks appears to be low, but significant, on CPUE and catch composition • Difficult to enforce in high seas fisheries • Some fishers avoid using light sticks because they believe it increases catch rates of sharks • LEDs have a similar intended effectiveness than chemical light sticks but may have less environmental impact if batteries are stored and disposed of ashore correctly • Eco-toxicological tests showed toxicity of chemical light-sticks for marine organisms, especially under low dilution conditions or direct contact.	(Alessandro and Antonello, 2010; Berkeley et al., 1983; Bigelow et al., 1999; Bromhead et al., 2012; de Oliveira et al., 2014; Gless et al., 2008; Hazin et al., 2005; Ivar do Sul et al., 2009; Lohmann et al., 2006; Pinho et al., 2009; Poisson et al., 2010; Santos et al., 2009; Wang et al., 2007)
	Prohibition of wire leaders (only nylon allowed) SWO: **19** TUN: **19** SHK: **11**	• Reduced numbers of sharks brought to vessel (bite through). • Saved time through reduced handling of sharks. • Catch rates of other valuable tuna and billfish species are higher on nylon than on wire leaders. • Easy to implement • The reduced interactions with live sharks reduces the risk for the crew.		• The use of wire leaders is considered indicating shark targeting as it is known to significantly increase the retention of sharks. • Already implemented in some areas. • Fishers acknowledge that wire leaders were often deployed to reduce gear loss from sharks. • Nylon leaders catch more bigeye tuna, *Thunnus obesus* and all target species combined, while wire leaders catch more blue shark, *Prionace glauca* and all sharks combined • The fate of escaped animals hooked on nylon traces is not known. Need for more studies for better understanding of the impacts on other groups of animals.	(Afonso et al., 2012; clarke, 2011; Kirby and Ward, 2014; SPC-OFP, 2013; Stone and Dixon, 2001; Ward et al., 2008)
	Circle hooks (no J-hooks, which tend to be fully ingested more frequently and thus likely to increase post-release mortality and no circle	• Reduced at-vessel mortality of sharks compared to J-hooks • Reduced catch rates of	• Conflicting results concerning potential reductions in catch rates of target species. • Potential increases in bycatch	• Already implemented in some areas and fisheries • Effect on shark survivorship is not fully known • Reduction of sea turtle interactions: the use of circle hooks has conservation benefits for sea	(Epperly et al., 2012; Fernandez-Carvalho et al., 2015; Ferrari and Kotas, 2013; Forney

Table 3. Continued.

	hooks, which are more frequently hooked in the jaw) SWO: **11** TUN: **11** SHK: **11**	pelagic stingray • Reduced impact on crocodile shark and small sharks • Hooking location of circle hooks can lead to a decrease in postrelease mortality of incidentally caught species • Any sharks to be retained may be of better quality • Easy to implement	of some species (including sharks). • Comparisons between hook types have shown varied results between fisheries, and species, so measure may be ineffective • Fishers have suggested that baiting circle hook is more time consuming. • Additional cost for fishers if mandatory measures brought in without warning	turtles; J-hooks and tuna hooks have a much greater probability of being swallowed than circle hooks. In addition, as the hook size increases, the likelihood of swallowing decreases • The use of circle hooks has conservation benefits for billfish; they may catch fewer sea birds than those sets using J-hooks; potential reduction in the overall rate of marine mammal interactions • Need to define a uniform system for hook characteristics and terminology • Notable difference in the experimental designs of the published studies • Need to understand the role of all operational characteristics in gear performance analysis • Need for improved species-specific controlled experiments to provide more definitive results • Catch-and-release studies have revealed that one of the strongest correlations of mortality for fishes is deep hooking in body organs such as the oesophagus, gills, or stomach, which is largely influenced by hook choice. • Making the use of circle hooks mandatory could affect shark catchability. In the event that it increased the number of sharks hooked, this may offset any improved escape rate or postrelease survival. • Time series of fishery-dependent CPUE data used in some stock assessments may be compromised	et al., 2011; Galeana-Villasenor et al., 2008; Godin et al., 2012; Graves and Horodysky, 2008; Graves et al., 2012; Kaplan et al., 2007; Moazzam and Nawaz, 2014; Murua et al., 2013; Pacheco et al., 2011; Piovano et al., 2009; Prince et al., 2002; Prince et al., 2007a; Read, 2007; Rice et al., 2012; Richards et al., 2012; Rudershausen et al., 2012; Sales et al., 2010; Sauls and Ayala, 2012; Serafy et al., 2012; Serafy et al., 2009; Stokes et al., 2011; Ward et al., 2009; Watson et al., 2005; Wilson and Diaz, 2012; Yokota et al., 2006; Yokota et al., 2012)
	Corrodible hook **11**	• Lower cost than stainless steel hooks. • Easy to implement and adopted by the fishing industry. • Could reduce long-term health impact (infections) if bitten off by a shark.	• The fate of escaped animals is not known	• The economic impact of adopting corrodible hooks requires a thorough assessment, as these hooks would need to be replaced more often than the low-grade stainless steel hooks currently used in fishing operations.	(McGrath et al., 2011; Patterson and Tudman, 2009)
	Weak hook (circle hooks with smaller diameter wire) **15**	• Possible reduction of the incidental catch of larger sharks	• The ability of weak hooks to release large fish alive and in good condition is questionable • Potential loss of large individuals of other commercial species	• The economic impact of adopting weak hooks requires a thorough assessment, as these hooks would need to be replaced more often than the low-grade stainless steel hooks currently used in fishing operations.	(NMFS, 2009)

Table 3. Continued.

	Increase in hook size **10**	• Possible reduction of the incidental catch of unwanted species	• Potential reduction in catches of some target species.	• Efficiency of the measure needs to be accessed as it may impact target species catches	(Piovano et al., 2009)
	Artificial bait SWO: **17** TUN: **17** SHK: **17**	• Possible increase the species-selectivity of the gear • Possible reduction of shark, sea turtle, bird, marine mammal bycatch • Reduce or stabilize the overall cost of bait through improved gear efficiency (e.g. by reducing bait lost during soak time) • Costs and supply less variable than natural bait • Possible reduction of the pressure on species exploited for bait	• Potential impact on catch rates of target species. • could induce additional time to bait the line. • Artificial baits may have their own environmental impact.	• Necessity to use eco-friendly material • Could also be consideration of using fish waste and other sub-products as bait	(Erickson and Berkeley, 2008; Garcia-Cortes et al., 2009.; Gilman et al., 2007; Tryggvadottir et al., 2002.; Bach et al., 2012)
	Fish not squid bait SWO: **5** TUN: **13** SHK: **8**	• Potential reduction in bycatch of some shark species • Reduced sea turtle bycatch	• Mackerel bait attracts sharks. • Conflicting results concerning the reduction of target species catch rates and the increases of some bycatchspecies (especially for elasmobranch species). • Possible reduction in fishery revenue when mackerel was used instead of squid. • Decreased exploitation cost as squid can be the more expensive bait used in these fisheries.	• Improved studies to understand the combination of hook type/size and bait type in relation to catch rates by species (and size) needs to be considered • May be difficult to control on-board • The effectiveness of this method could be species-, fishery- and geographically-specific	(Coelho et al., 2012; Fernandez-Carvalho et al., 2015; Foster et al., 2012; Gilman et al., 2008)
	Magnetic, E+ metals, electrical deterrents **7**	• Potential reduction in bycatch of shark species	• The impact on the target species often unknown • These devices are fragile, costly and the method can be difficult to implement	• Conflicting results concerning the efficiency of magnetic deterrents from laboratory studies, especially in relation to possible habituation • There is not enough information on the effect that magnet and metal could have as repellent on	(Godin et al., 2013; McCutcheon and Kajiura, 2013; Meyer et al., 2005; O'Connell et al., 2010; O'Connell et al., 2011;

Table 3. Continued.

			• Pollution concerns • Health and safety concerns	pelagic sharks commonly caught by commercial longliners.	Rigg et al., 2009; Robbins et al., 2011; Stoner and Kaimmer, 2008; Swimmer et al., 2008; Tallack and Mandelman, 2009)
	Olfactory repellents **9**	• The use of chemical shark repellents like shark necromone seems to repel sharks	• Habituation may occur. • Pollution concerns.	• It is recognized that the method still requires a great deal of experimentation and evaluation, and runs the risk to attract or repel tuna or tuna-like species.	Sisneros and Nelson, 2001 ; Southwood et al., 2008 ; (Dagorn et al., 2010; Jordan et al., 2013; Sisneros and Nelson, 2001; Southwood et al., 2008; Stroud et al., 2014) (Hart and Collin, 2015)
	Auditory deterrents and attractors **9**	• Low frequency sounds have strong attractive effect on sharks.	• Devices deployed prior to the fishing operation including time and fuel gas consumption. • Difficult to implement in industrial fisheries due to gear size.	• Results have been promising, but more investigation and large-scale trials are required. Given the current limited state of its development, this method cannot be considered at the moment.	(Myrberg, 2001; Myrberg et al., 1969; Nelson, 1976; Nelson and Gruber, 1963; Southwood et al., 2008)
	Fleet communication **14**	See table 4 for details			(Gilman, 2011)
	Reduced soak time **10**	• Reduced catch of sharks • Decrease in at-vessel mortality and potential increase in postrelease survival of discarded bycatch • Improved quality of the target species • Potential reduction in the depredation of target species	• Potential for reduced catches of target species. • Negative impacts on fisher safety if it reduces the resting time for the crew. • Difficult to monitor as the haulback time (and so the soak time) increases with quantity of fish caught.	• Optimal soak time likely varies by fishery. • The organisation of work according to a certain pattern must take account of the general principle of adapting work to the crew • Increased vitality of some species caught could increase processing time and affect crew safety. • Swordfish catch did not increase with longer soak times. • The longline gear is generally counter-retrieved; the first hook set is the last retrieved. The minimum soak time is the elapse time between the end of setting and the beginning of the hauling and the maximum soak time, from start of setting to end of hauling of the longline. While the setting duration and the drifting time of the line can be easily monitored the haulback time increase significantly with the number of fish caught.	(Carruthers et al., 2011; Erickson and Berkeley, 2008; Lokkeborg and Pina, 1997; Poisson et al., 2010; Ward and Myers, 2007)

Table 3. Continued.

				• Possible increase in fishing effort (i.e., increase in the number of sets) and consequently in bait requirements and fuel consumption	
	Prohibition of live bait **11**	• Improved CPUE of yellowfin and bigeye tunas	• May increase the bycatch rates (i.e. sharks, sea birds, billfish)	• This technique is used only in few areas and applies to a limited number of fisheries • Farmed milkfish *Chanos chanos* is a common commercial bait of longline fisheries in some Asian countries. • The use of live bait is already banned in several countries. • Could impact the current activity of the fish farming. • The effects on bycatch rates have not been assessed.	(FitzGerald, 2004; NMFS, 2008)
	Deep setting **SWO: 7** **TUN: 14** **SHK: 7**	• Reduction in the bycatch of those sharks living in the upper water column. • Reduced sea turtle bycatch.	• Risk of increasing catches of deeper-dwelling shark species in some areas • Technically difficult to reach the desired depth. • May result in higher mortality rates for fish caught (barotrauma) • May cause increased discarding of other species.	• Shifting fishing effort into deeper water can be a risky response to the decline in shallow coastal water resources	(Beverly and Robinson, 2004; Cambiè et al., 2013; Patterson and Tudman, 2009; Walsh et al., 2009; Watson and Bigelow, 2014)
	Management of offal discharge **12**	• Potential reduction in catches of scavenging species such as sharks. • Reduced interactions with seabirds. • Easy to implement with no extra cost. • Positive support from the fishing industry.	• Measure may require greater observer coverage to encourage uptake and to develop best practice.	• Little is known of the impact upon shark catch rates of these practices.	(Gilman et al., 2008)

Table 3. Continued.

Fishing practice /strategy	**Restricting fishing on topographic and oceanic features** **10**	• Areas of high elasmobranch abundance can be avoided. • Some areas may be associated with physical features and such sites can be designated easily.	• Such areas may also be used by target species. • Difficult to enforce in high seas. • Some productive areas may be associated with oceanographic features and so have varying degrees of spatio-temporal fidelity • If legal fisheries avoid such sites, then they may be exploited more by IUU fisheries • May increase steaming times for some vessels	• More comprehensive studies on the distribution and behaviour of sharks and target species in relation to oceanographic and topographic features required.	(Bigelow et al., 1999; Gilman et al., 2007; Watson et al., 2005)
Practices to increase survival rates	**Enforcement of the protocols of safe handling and release** **14**	• Improved safety for crews. • Effective measure for species with low at-vessel mortality. • May improve post-release survival, including for species which currently have a high discard mortality. • Easy to implement with relatively little expense • Positive support from the fishing industry as it could be implemented with little expense.	• Mandatory measures can require high levels of observer coverage. • Ability to have optimal handling of sharks may be compromised on some vessels by the design of the deck.	• Booklet dedicated to skippers and crews, presenting the good practices should be developed initially • Monitoring the uptake and implementation of these practices is necessary • Further research on shark stress and postrelease mortality could help in improving handling practices • To improve the crews' awareness of the bycatch issue, one deckhand could be designated "Bycatch manager" to coordinate good bycatch practices on-board.	(Carruthers et al., 2011; Patterson and Tudman, 2009)
	Mandatory safe handling equipment for sharks and turtles (de-hooker, mouth opener, bolt cutter, line cutter with long handle, dipnet). **13**	• Improved safety for crews. • Reduced postrelease mortality of sharks and other sensitive species • Positive support from the fishing industry. • Allows crew to safely discard pelagic stingray and recover hooks.	• Uptake of such tools can require appropriate training and education programmes and sufficient levels of observer coverage	• Already implemented in some fisheries • Monitoring the implementation of these practices onboard is necessary	(Carruthers et al., 2011)
	Workshop/Trainings **13**	See table 4 for details			

Table 3. Continued.

Tropical tuna purse seine fisheries

Mitigation category	Mitigation Measure	Advantages	Disadvantages	Remarks	Source
Fishing Gear modifications	**Prohibition of Entangling FADs** **17**	• Reduction of the probability for sharks and sea turtles to get entangled in the DFADs (ghost fishing). • Reduction of synthetic material debris. • Easy to implement. • Positive support from the fishing industry if the efficiency of this device is guaranteed.	• The cost of such DFADs is higher than a "regular" one. • Shorter lifespan.	• Guidelines for non-entangling DFADs has been developed by ISSF	(Anonymous, 2013; Dagorn et al. , 2010; Filmalter et al. , 2013; Franco et al. , 2009)
	Mandatory use of hopper **15**	• Increased retention of large sharks and other bycatch on the upper deck, so facilitating safe handling and live release. • No impact on the target species	• Potential cost of modifying vessel design if structural changes required	• Redesigning the hopper is required to improve the retention of small sharks.	(Poisson et al., 2014b)
	Release panels for shark **10**	• Reduced catch of sharks. • No impact on the target species. • Positive support from the fishing industry if the efficiency of this device is guaranteed. • Reduced interactions with sharks and reduced risks of accident for the crew.	• Needs modifications to the purse seine net, which could discourage fishers • Difficult to implement/enforce as it can increase the time of the fishing operation.	• Promising approach which needs further refinements of this concept with additional testing and experimentation.	(Itano et al., 2012)
	Improved conveyor belt and waste chute design **13**	• Potential way to reduce damage on sharks (and other bycatch) and post-release mortality. • Authorize a quick release directly from the lower deck • Positive support from the fishing industry as it could be possible to redesign the system • Fishers could then voluntarily adopt this practice.		• These devices are not standardized and their shape and location vary. • Improved design of such systems would likely improve discard survival of bycatch. • The conveyor belts currently on vessels can be an obstacle to cross for the crew when they want to release sharks. Most of the time, crews are reluctant to leave their workstation to release sharks from the upper deck. • The postrelease survival of the shark released through this device is unknown.	(Poisson et al., 2014b)

Table 3. Continued.

Fishing practices/strategy	**Setting on bigger aggregations** **11**	• Reduced total bycatch • Easy to implement as skippers are able to determine the size of the aggregation prior to setting net. • Positive support from the fishing industry as this method could be used in conjunction with other incentive based systems. • Easy to control with logbook and observer data	• Only moderate effects on the total bycatch. • Difficult to implement/enforce in the absence of appropriate observer coverage.	• Fishers could adopt this measure voluntarily when approaching a pre-determined seasonal bycatch quota, but wish to continue catching tuna.	(Dagorn et al., 2012)
	DFAD monitoring or management plan **5**	• Reduction of total bycatch	• Strong opposition of the fishing industry. • Increased fuel consumption while increasing searching time.	• Deploying a greater number of DFADs in the water does not necessarily help fishers to catch more tuna, but does increase the level of fishing effort and bycatch.	(Dagorn et al., 2013; Sempo et al. , 2013; SPC, 2009)
	Ban of supply vessels **9**	• Reduction of the number of FADs deployed		• In the Pacific Ocean, it has already been proposed to prohibit the use of tender vessels operating in support of vessels fishing on DFADs. • Only few fisheries are using supply vessels.	(Arrizabalaga et al., 2001; Dagorn et al. , 2013)
	Towing DFAD out of net after encirclement **12**	• Potential reduction of shark bycatch • Release of the community associated with the FAD alive	• No evidence of the shark behaviour. • Risk for fishers if tunas are seen or thought to escape from the net.	• Promising approach which needs further refinements of the concept with additional testing and experimentation.	(Hall and Roman, 2013)
	Multiple FADs **11**	• Potential reduction of shark bycatch.	• Not enough information at the moment.	• More investigation on the measure at large-scale trials required.	(Schaefer and Fuller, 2011)

Table 3. Continued.

	Use bait station **6**	• Potential reduction of shark bycatch.	• Not enough information at the moment.	• The key questions for this study are: 1) whether the bait station is more attractive to the sharks than a FAD; 2) whether the sharks can be attracted without the tunas being attracted as well; and 3) whether the use of bait stations is practical and efficient within the constraints of a purse-seine fishing.	(anonymous, 2007; Kondel and Rusin, 2007; Scott, 2007)
	Restriction of setting on whale sharks and marine mammals **13**	• Reduced safety risks for crew • Reduced postrelease mortality of sharks and other sensitive species • Reduced net damage • Reduced time spent handling megafauna • Easy to implement • Positive support from the fishing industry • Easy to control with logbook and observers data	• Moderate improvement of present situation since whale sharks (and marine mammals) are released alive in the majority of cases without being brought on-board. • Difficult to implement/enforce in the absence of appropriate observer coverage.	• Some t-RFMOs adopted measures to prohibit setting intentionally on whale shark and to release unharmed accidental bycatch (WCPFC CMM 12-04, IOTC Res. 13-05, IATTC C13-04).	(anonymous, 2007, 2010; Capietto et al., 2014; clarke, 2011; Speed et al., 2008)
Practices to increase survival rates	**Enforcement of the protocols of safe handling and release** **16**	• Improvement of the safety for the crew. • Effective measure especially for species with low at-hauling mortality. • Reduction of the shark post-release mortality. • Easy to implement with relatively little expense • Positive support from the fishing industry	• Uptake of such tools can require appropriate training and education programmes and sufficient levels of observer coverage	A first version of good practices • has been developed for the EU purse seiner fleet and can be adopted for other fisheries. • A study shows that if sharks are released as rapidly as possible and handled in a good manner, by-catch mortality of silky sharks can be reduced by 15% in the fishery • More investigations on at-vessel mortality required	(Poisson et al., 2014a; Poisson et al., 2014b; Poisson et al., 2012)
	Workshop/Training **13**	See table 4 for details			

Table 3. Continued.

Drift and gillnet fisheries

Mitigation category	Mitigation Measure	Advantage	Disadvantage	Remarks	Source
Fishing Gear modifications	**Modify mesh slack** **5**	• Improvement of the survivorship at hauling but not the number of interactions • Reduction of gillnet damage caused by wrapped sharks. • Reduction of sharks bycatch without having a deleterious effect on target catch rates in the case of anchored gillnet targeting Spanish mackerel (*Scomberomorus maculatus*) and spot (*Leiostomus xanthurus*)	• A maximum size limit may be useful as it will protect the breeding stock and larger sharks likely have a better chance of surviving after being captured. • It does not change the number of interactions • Marine mammals (i.e. seals) can be affected by gear changes	• Modification on a case by case basis could hinder their ability to retain sharks	(Hovgård and Lassen, 2000; McAuley et al., 2007; Patterson and Tudman, 2009; Thorpe and Frierson, 2009)
	Magnetic, E+ metals, electrical deterrent 1	• The use of ferrite magnet blocks appears to repel sharks. • No reaction behavior of the barramundi *Lates calcarifer* to magnetic fields.	• The size and weight of the magnets used here may pose difficulties with attaching them to nets while maintaining the fishing integrity and buoyancy of the net in the water	•More research is needed	(Rigg et al., 2009)
	Use turtle/shark lights	• Illuminated nets may not only be useful in reducing sea turtle interactions with gillnets, but may also be a method of reducing scalloped hammerhead by-catch in gillnets.		• More research is needed to see the impact on sharks and rays	(Southwood et al., 2008; Wang et al., 2007)
Fishing practices/strategy	**Reduced soak time** 8	Shorter soak times would likely increase the survivorship but could increase the number of interactions if the effort is not limited. Optimal soaking duration likely varies by fishery	• Negative impacts on fisher safety if it reduces the resting time for the crew.	• As fishers would be moving their gear around more, this would potentially increase the number of interactions. A reduced soak time would be difficult to monitor and ensure compliance	(Carruthers et al., 2011; Frick et al., 2012; Patterson and Tudman, 2009)
	Fleet communication **14**	See table 4 for details			
	Restricted setting time **7**	• Shark species generally spend more time near the surface at night which could result in an increase of sharks caught when night setting.		• Optimal setting time duration likely varies by fishery. • More research is needed	(Patterson and Tudman, 2009)
Practices to increase survival rates	**Enforcement of the protocols of safe handling and release** 16	• see above			(Carruthers et al., 2011; Frick et al., 2012)

Table 3. Continued.

Recreational fisheries

Mitigation category	Mitigation Measure	Advantage	Disadvantage	Remarks	Source
Fishing Gear modifications	Circle hooks See above 11	• Increased postrelease survival			(Cooke and Suski, 2005; Cooke et al., 2012; Serafy et al., 2012; Wilson and Diaz, 2012).
Fishing practices/strategy	Prohibition of live bait See above 11	• Reduced interactions with sharks and other bycatch, including sea birds			(Prince et al., 2007b)
	Fleet communication 12	See table 5 for details			
Practices to increase survival rates	Enforcement of the protocols of safe handling and release See above 14	Increased postrelease survival		• Given the emphasis on tag-and-release strategy, it is important to gain some understanding of postrelease behavior and mortality. • the mode of capture shark can affect mortality (e.g. common thresher) • angler education programmes that have tried to promote voluntary changes in angler behavior have shown promise in some inland fisheries	(Cooke and Suski, 2005; Cooke et al., 2012; Kneebone et al., 2013; Pepperell and Davis, 1999; Sepulveda et al., 2015)
	Workshop/training 13	See table 4 for details		• As recreational angling continues to grow in popularity, expanding to many developing countries, and targeting alternative species, it is important that reasonable data appropriate for specific fish and fisheries are available. The sustainable use and conservation of recreational fishery resources depends on the development and dissemination of effective and practical catch-and-release angling protocols developed with stakeholders. Species-specific guidelines for catch-and-release are needed, considering the diversity of species and variation in fishing techniques.	(Fowler and Partridge, 2012; Lynch et al., 2010; NOAA., 2009)

Table 4. Summary of advantages and disadvantages of general technical mitigation measures for elasmobranch bycatch in tuna and tuna-like fisheries.

Mitigation measure	Advantage	Disadvantage	Remarks	Source
Develop real-time fleet communication programme	• Can report real-time observations of bycatch hotspots to be avoided by other vessels • Helps avoid hotspots of sharks and other taxa • Easy to implement	• Difficult to monitor. • Avoiding bycatch hotspots may be compromised by catch rates of target species.	• May be successful if there is no competition for target fish, strong economic incentives to reduce depredation, bycatch and interactions with unwanted species • Support from the fishing industry because economic costs potentially low and allows them to demonstrate environmental awareness	(Gilman et al. 2008; Gilman et al. 2006)
Workshops and training programmes on good handling and fishing practices, and species identification	• Improved safety for crews • Reduced mortality of discarded elasmobranchs and other sensitive species • Potential time savings • Raise the fishers' awareness of conservation issues and encourage their participation in the sustainable management of marine resources	• Potential for fishers to incur costs when attending workshops compromising participation. • Some good handling practices may increase the time taken to bring fish onboard or catch-processing time.	• Regional workshops for fishers and observers could be organized to review various mitigation methods and fishing practices to reduce mortality of bycatch species • Could be run alongside observer programmes • Protocols for good handling and release shared, in order to ensure the safety of the crew and optimize the survival of released animals. • Species identification workshops can help ensure correct species catch recording • Possible support from of these measures if they receive some subsidies in return	(Carruthers et al. 2011; Poisson et al. 2014; Poisson et al. 2012)

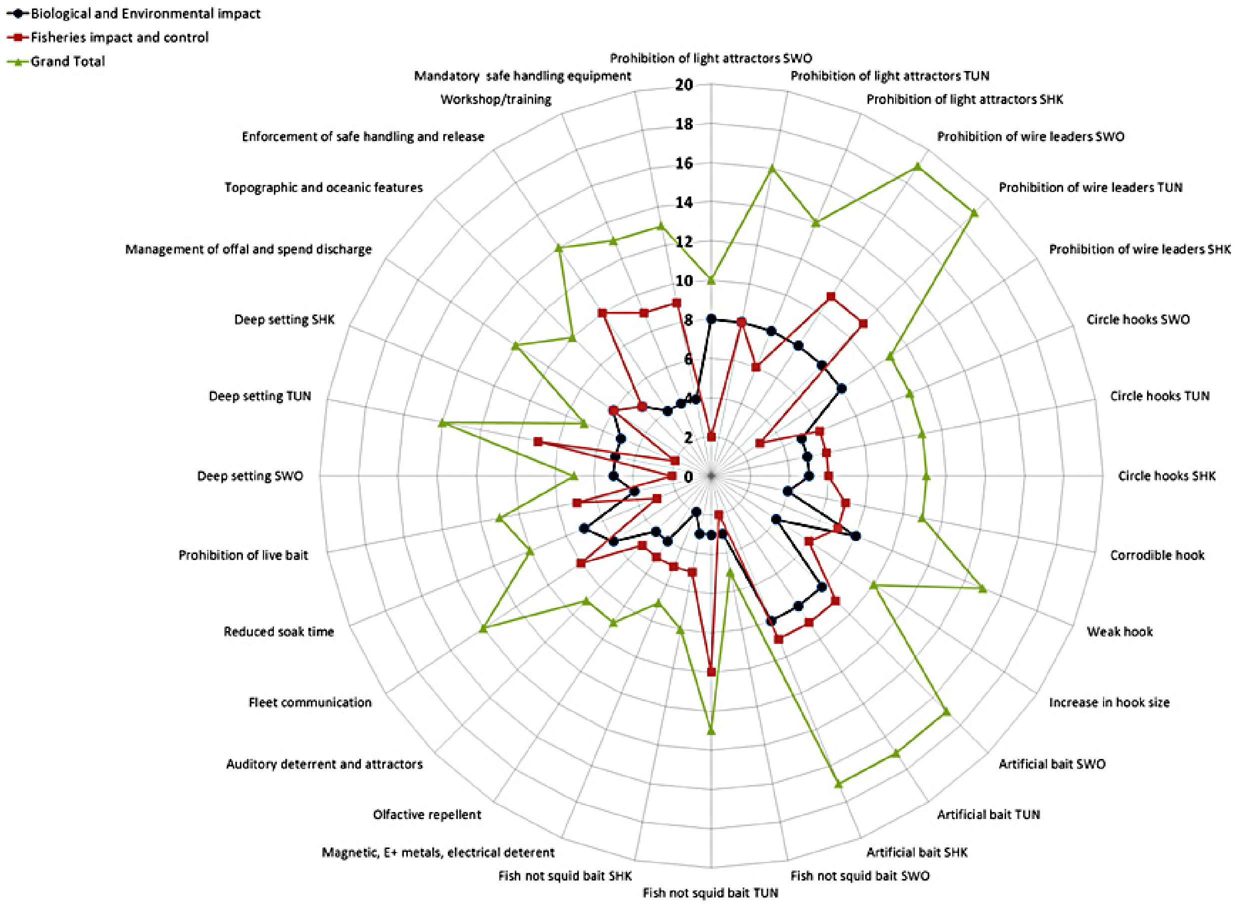

Fig. 1. Mitigation options to reduce elasmobranch bycatch and ranking against criteria for longlines (SWO swordfish longline; TUN tuna longline; SHK shark longline).

Based on our review and assessment we can classify MMs for longline fisheries into three groups. The first group contains MMs supported by fishers as they have no impact on the yield of their target species. This group includes seven measures: "Prohibition of wire leaders", "Prohibition of light attractors", "Fish not squid bait", "Deep setting", "Prohibition of the use of live bait", "Reduced soak time", and "Restricting fishing on topographic and oceanic features". The second group of MMs is acceptable by all longline fisheries because they are easy to implement at relatively low costs: "Circle hooks", "Corrodible hook", "Weak hook", "Increase in hook size" "Enforcement of safe handling and release", "Workshop/training", "Mandatory sea turtle/sharks safe handling equipment", "Management of offal and spend discharge", and "Fleet communication". The third group of MMs is theoretically attractive but they have never been successfully tested in the field: "Artificial bait", "Magnetic, electropositive or electrical deterrents", "Olfactory repellents", and "Auditory deterrents/attractors".

3.4 Mitigation measures for tuna purse seine fisheries

Thirteen MMs were identified for purse seine fisheries, including measures pertaining to "Fishing gear modification" (four MMs), "Fishing practices and strategy" (seven MMs) and the "Practices to increase survival rates after release" (two MMs) categories. Overall scores ranged from 5 to17 (Fig. 2, Table S2db).

Among the MMs from the first category, the most promising were "Prohibition of entangling DFADs (Drifting fish aggregating devices)" (score = 17), which has already been field-tested and has been implemented in some fleets (*e.g.* EU purse seine fleet), the "Mandatory use of a hopper" (score = 15), which could be applied very quickly, and "Improved conveyor belt and waste chute design" (score = 13), which could be developed in a relatively short time with the help of fishing gear technologists. Two of these MMs ("Mandatory use of a hopper" and "Improved conveyor belt and waste chute design") scored highly, as they are already in place on certain vessels, have been tested successfully in the field, and have been welcomed by some sectors of the fishing industry. Other potential MMs, such as a "Release panel for sharks" (score = 10) are still in developmental stages.

Among the measures related to the "Fishing strategy and practices" category, "Restrictions of setting on whale sharks" (score = 13) are already in place in the Pacific and Indian Oceans and preferring "Setting on bigger aggregations" (score = 11) is already practiced by some skippers who are concerned about potential loss of time, risks to crew, and as a way of reducing bycatch.

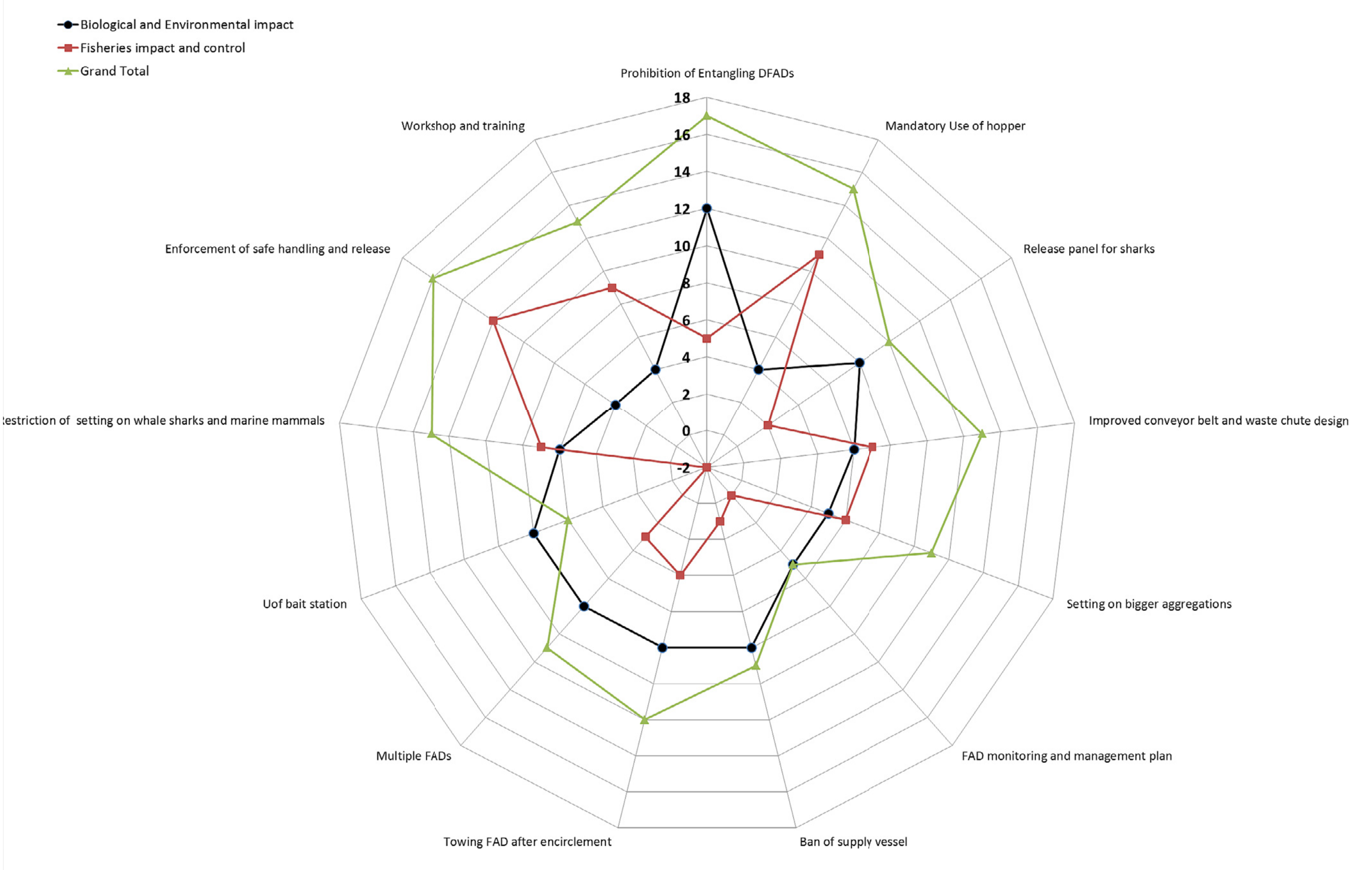

Fig. 2. Mitigation options to reduce elasmobranch bycatch and ranking against criteria for tropical tuna purse seiners.

The measures "Towing DFADs out of the net after encirclement", "Multiple DFADs", and "Bait station" showed some promises (scores = 12, 11 and 6, respectively), but further field work is needed before their implementation.

Overall, measures such as "DFAD monitoring and management plan" and "Ban of supply vessel", which could increase fuel consumption due to increased searching times if the number of DFADs was restricted, would affect the operations of the fishing industry, and so ranked poorly (score = 5 and 9, respectively).

3.5 Driftnet and gillnet fisheries

Eight MMs were identified for these fisheries, covering "Fishing gear modifications" and "Fishing strategy and practices" (three MMs each), and "Practices to reduce mortality" (two MMs) (Fig. 3, Table S2dc).

"Turtle /shark lights" scored only 7, as more research on their effectiveness is required before they could be considered for wider implementation. The option "Modify mesh slack", which could theoretically improve survivorship and would not reduce the interactions, only scored 5, due to insufficient evidence as to its effectiveness. "Magnetic, electropositive or electrical deterrents" did not seem to show any clear advantages (score = 1). Of the MMs influencing fishing practices, the option for "Fleet communication" ranked top (score = 14) whilst "Restricted setting time" and "Reduced soak time" scored 7 and 8, respectively. "Enforcement of safe handling and release" and Workshop/training" scored 14 and 13 respectively.

3.6 Recreational fisheries

Five MMs were identified for recreational fisheries, "Practices to increase survival rates after release" and "Fishing strategy and practices" (two MMs each) and "Fishing gear modifications" (single MMs) (Fig. 4, Table S2d). "Fleet communication" scored 12; "Enforcement of safe handling and release" and Workshop/training" scored 14 and 13 respectively.

4 Assessment of the survival of elasmobranchs in fisheries for tuna and tuna-like species fisheries

4.1 At-vessel mortality

4.1.1 Longline fisheries

The results of 16 studies (published from 1992–2013) examining mortality associated with pelagic longline gears were collated. To date, at-vessel mortality has been estimated for 23

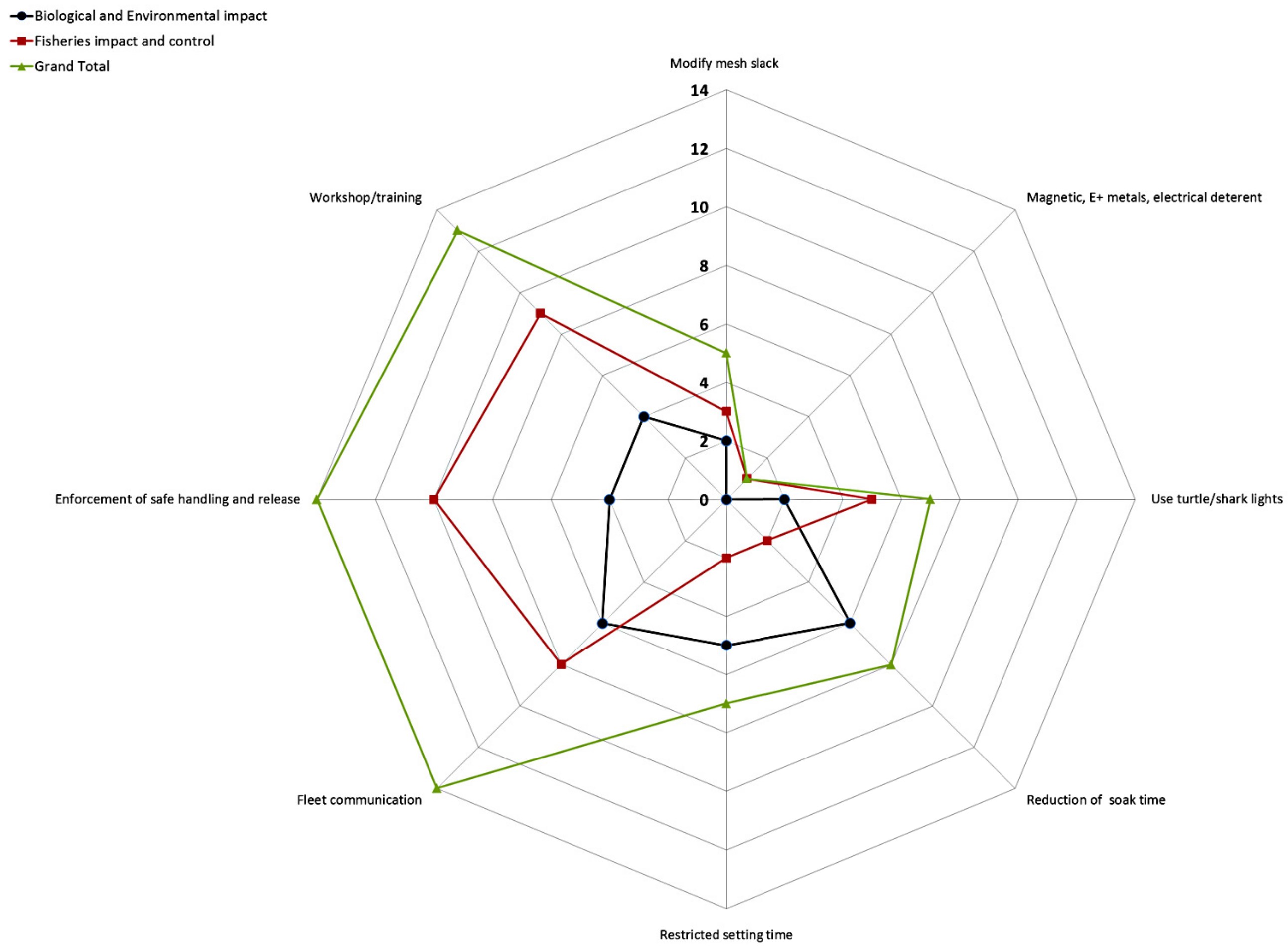

Fig. 3. Mitigation options to reduce elasmobranch bycatch and ranking against criteria for tuna gillnets.

species or groups (Table S1). Most of them have studied blue shark *Prionace glauca*, the most common shark species taken as bycatch in longline fisheries (13 papers), followed by shortfin mako *Isurus oxyrinchus* (nine papers), oceanic whitetip shark *Carcharhinus longimanus* (eight papers), silky shark *Carcharhinus falciformis* (six papers), tiger shark *Galeocerdo cuvier*, bigeye thresher *Alopias superciliosus* (four papers) and scalloped hammerhead *Sphyrna lewini* (four papers) and common thresher *Alopias vulpinus* (three papers).

At-vessel mortality is often species-specific, with some species (e.g. tiger shark, blue shark, sandbar shark, pelagic stingray and mobulid rays) appearing to be relatively hardy, whilst hammerhead sharks, thresher sharks and some carcharhinid sharks (including silky shark, blacktip shark and night shark) tend to have higher mortality rates.

A large range of at-vessel mortality rates have been reported for blue shark, their vitality varying widely, depending on the gear, fishing strategy and handling practices (Campana et al. 2009), and potentially between observers. Estimates of at-vessel mortality for blue shark taken in swordfish fisheries were often in the range of 12–16% (Campana et al. 2009; Coelho et al. 2012b); but could be as high as 51% (Poisson et al. 2010). In the case of tuna fisheries or mixed swordfish/tuna fisheries, at-vessel mortality ranged from 0–31% (Boggs 1992; Francis et al. 2001; Beerkircher et al. 2002; Hight et al. 2007; Afonso et al. 2011, 2012; Bromhead et al. 2012). For silky sharks, estimates of at-vessel mortality rate in the swordfish longline fishery varied from 11% (Musyl et al. 2011) to 55.8 and 66.3% (Beerkircher et al. 2002; Coelho et al. 2012a).

The use of circle hooks appears to reduce the at-vessel mortality for most species caught in pelagic longline fisheries (Afonso et al. 2011). Afonso et al. (2011) and Watson and Bigelow (2014) also showed that changing the type of hook and removing the shallowest hooks for daytime longline sets targeting albacore tuna can significantly reduce the level of interactions with sharks.

Shark size can also be an important factor for estimating mortality rates, as smaller sharks generally suffer higher mortality in longline fisheries (Coelho et al. 2012a, 2013). The whole fishing process along with handling practices are obviously major factors to consider.

4.1.2 Tropical tuna purse seine fisheries

Silky shark is the most frequent elasmobranch bycatch species in tropical tuna purse seine fisheries (Amande et al. 2010). Three studies (published between 2014 and 2016)

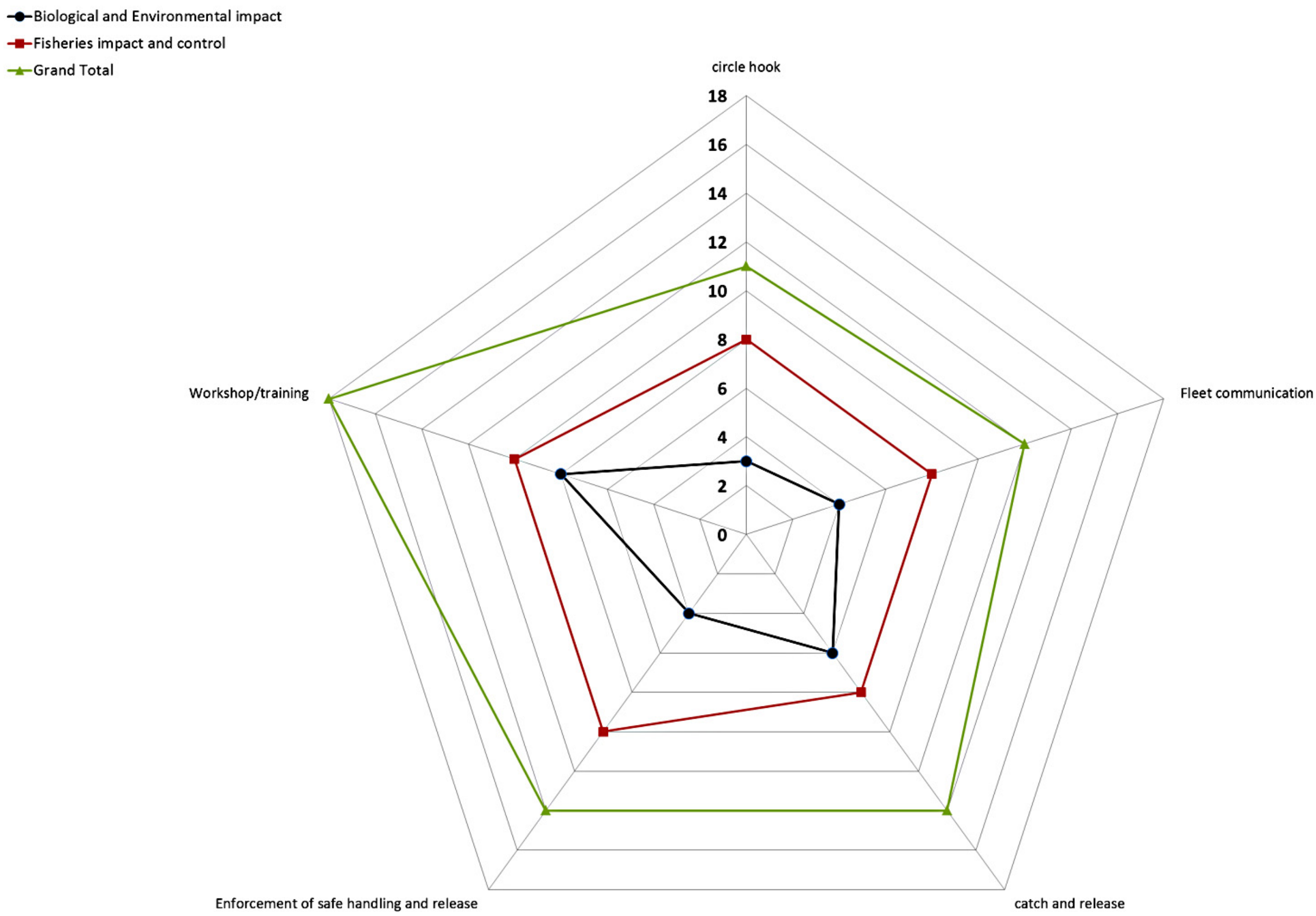

Fig. 4. Mitigation options to reduce elasmobranch bycatch and ranking against criteria for recreational fisheries and rod and reel tuna fisheries.

examined the mortality of this species associated with this gear. The high estimates of silky shark's at-vessel mortality (59–69%) and high estimates of overall mortality rates (81–95%) reflect the harsh conditions encountered by sharks during purse seine fishing operations in the western and central Pacific Ocean (Hutchinson et al. 2015) and in the Indian Ocean (Poisson et al. 2014a). The at-vessel-mortality rate recorded for this species in the Eastern Pacific Ocean (Eddy et al. 2016) was lower (59%).

4.1.3 Gillnets fisheries

Three studies examined mortality associated with gillnets, through experimental fishing. To date, at-vessel mortality has been estimated for five species: results range from 80.4% for sharpnose sharks (*Rhizoprionodon terraenovae*) and 91.3% for blacknose sharks (*Carcharhinus acronotus*) (Thorpe and Frierson 2009) to a relatively low level of 18.5% for bull shark (*Carcharhinus leucas*) (Manire et al. 2001). For other species, estimates of at-vessel mortality varied substantially, 24.2–90.5% for blacktip sharks (*Carcharhinus limbatus*) and 30.8–71.5% for bonnethead sharks (*Sphyrna tiburo*). The high estimates of at-vessel mortality reflect the traumatic conditions during net entanglement and struggling after capture, with corresponding high overall mortality rates of 62 and 78.6% all species combined.

As in longline fisheries, capture in gillnets restricts mobility and can result in exhaustive anaerobic exercise (the soak times for some industrial fishing operations can exceed 20 h), as well as reduce the ability for ram ventilation of the gills, so exacerbate mortality of ram-ventilating pelagic sharks (Thorpe and Frierson 2009).

4.2 Postrelease survival (PRS)

The most effective approach for monitoring PRS is through the use of electronic tags, such as Pop-up Satellite Archival Tags (PSATs). Whilst this approach provides excellent data on the behavior of sharks after release, the costs involved often result in small sample sizes. Therefore, few studies using this technology have been undertaken; three in the case of longline fisheries and only on blue shark either on-board commercial vessel (n = 40) (Campana et al. 2009), or during research cruises (n = 23) (Moyes et al. 2006) and (n = 16) (Musyl et al. 2011). The PRS for this species were high, ranging between 85 and 100%.

In the case of purse seine fisheries, PRS was estimated for three species. For silky sharks, Hutchinson et al. (2015) reported a PRS rate of 15.8% (n = 28), Poisson et al. (2014a) a PRS rate of 52% (n = 31) and Eddy et al. (2016) a PRS rate of 28% (n = 13). Despite these differences, the total mortality rate observed in the equatorial eastern Pacific Ocean (EPO) (92%) was comparable to the value obtained in the Indian Ocean (81%) (Poisson et al. 2014a) and in the West and Central Pacific Ocean (84%) (Hutchinson et al. 2015). Francis (2014) reported a PRS rate of 75% for spinetail devil ray *Mobula japanica* (n = 6) and Eddy et al. (2016) a PRS null for scalloped hammerhead *Sphyrna lewini.*

In recreational fisheries, "Catch and release" practices are intended to be a technique of conservation. Two publications showed that the mode of capture of common thresher shark can affect mortality. Fish hooked through the mouth (mouth-based angling techniques) and subject to careful handling and release techniques exhibited a PRS of 100% after 10 days (n = 7) (Sepulveda et al. 2015). The use of the caudal-based angling technique induced a lower PRS due to the fact that this technique reduced ability for forward locomotion and ram ventilation. The PRS ranged from 74% (Heberer et al. 2010); n = 19) to as low as 22% (Sepulveda et al. 2015); n = 9). Large individuals (≥180 cm FL) with fight times ≥85 min experienced high mortality.

5 Discussion and future directions

This study provided a broad overview of available data, publications and reports on MMs that may be applicable to various pelagic fisheries for tuna and tuna-like species with the aims to help fisheries managers identifying the more appropriate solutions to reducing elasmobranch bycatch fishing mortality, whilst minimizing impacts on other groups and yield of target species.

For the main gears used in high seas tuna fisheries, the various management options were assessed qualitatively against a suite of criteria and ranked based on the information found in the literature and the authors' expertise. Implementation costs, feasibility, and applicability of the measures from the stakeholders' perspective were all considered. The first priority for the main gears used in high seas pelagic fisheries is to avoid catching sharks and, when bycatch occurs, to minimize their mortality. Some generic MMs can be applied to all fisheries, but many options are fishery-specific.

5.1 The paucity of new solutions for longline gears targeting tuna-like species to reduce shark mortality

Over the last decade, most peer-reviewed studies on technical MMs have focused on longline gears, which have high levels of bycatch for many shark species (Mandelman et al. 2008). Indeed, longline gears impact many shark and ray populations, with ca. 52% of the global shark catch ascribed to this type of gear (Worm et al. 2013). The present study indicates that the number of MMs to reduce mortality of sharks through gear modifications which could be implemented rapidly is limited. These include: "Prohibition of wire leaders", "Prohibition of light attractors" and "Use of corrodible hooks". The first measure may have economic implications and encounter resistance from those fleet segments for which sharks are an economically important catch or bycatch. Chemical light-sticks have been shown to negatively impact the environment (Ivar do Sul et al. 2009; Pinho et al. 2009; Santos et al. 2009; de Oliveira et al. 2014) and increase the probability of catching sharks (Bigelow et al. 1999) and sea turtles incidentally (Lohmann et al. 2006).

Modifications of fishing strategies need the support, acceptance and buy-in of fishers and vessel owners, as it is not currently practicable to have full observer coverage. Two MMs, "Prohibition of live bait" and "Fleet communication", could be introduced without further analysis. The fishing industry would likely be relatively supportive of these measures, as they are easy to implement at relatively little cost.

The "Use of circle hooks" (sometimes associated with a change of bait) has been considered as one of the more tangible and promising mitigation options, not only for sharks and rays but also for sea turtles. Indeed, the use of circle hook is already mandatory in some areas; e.g. circle hook use (offset ≤10°) was first made mandatory in mid-2004 for US commercial pelagic longline fishers operating in Atlantic waters (Serafy et al. 2009). There is an extensive scientific literature on this topic which shows that the results vary between species and fisheries. In some cases, increased catch rates of sharks with circle hooks have been reported (Watson et al. 2005; Ward et al. 2009; Sales et al. 2010; Domingo et al. 2012; Andraka et al. 2013), but postrelease mortality of elasmobranchs could be reduced. Given the contrasting results, this MM cannot be transferred automatically from one region to another without adequate trials on commercial vessels in the areas and fisheries of concern.

"Deep setting" (when swordfish is not targeted) and "Reduced soak time" need more research to be validated. Other potential MMs (e.g. weak hooks, increased hook size, artificial bait) require further development and assessment, using robustly-designed field experiments, to validate their potential effectiveness.

Pelagic fisheries either targeting commercially valuable sharks (e.g. shortfin mako) or for which sharks are a valuable bycatch may be reluctant to introduce certain MMs, and in such instances other more traditional management measures (e.g. quota, controls on fishing effort, size restrictions) may be more effective to ensure the sustainable exploitation of the target species. Management plans for fisheries targeting sharks are proposed in the WCPFC, with CMM 2014-05 indicating that Contracting Parties must develop a management plan for shark fisheries that includes specific authorization for fishing sharks (e.g. through license, quotas or other measure to limit catches to biologically acceptable levels). Further, longliners of the Contracting Party should comply with at least one of the following options: (i) not to use or carry wire traces as branch lines or leaders, or (ii) not to use branch lines running directly off the longline floats or drop lines, known as shark lines.

In some of the waters managed by the USA, the government has introduced restrictions on hook and bait type for the pelagic longline fleet that is permitted to fish for tunas and swordfish. Vessels should always use corrodible (i.e., non-stainless steel) of 18/0 or larger circle hooks with an offset not exceeding 10°, or 16/0 or larger non-offset circle hooks. Only whole finfish and/or squid bait may be used. In the Gulf of Mexico vessels carrying pelagic longline gear on-board can only possess, use, or deploy circle hooks that are constructed of round wire stock which should be ≤3.65 mm in diameter ("weak hooks"). The use of live bait is also prohibited (Anonymous 2014).

Several MMs based on attempting to make use of the acute sensory abilities of elasmobranchs (e.g. magnets, repellents) may be good in theory, but have unfortunately given mixed results in experiments and have not yet led to effective MMs in the fishery. Magnetic and electropositive metals were considered promising several years ago (Bazilchuk 2005; Gilman et al. 2008), but since then field experiments have been unable to demonstrate that such devices would be effective (Godin et al. 2013). Additionally, the costs are considered prohibitive outside experimental studies. Similarly, MMs that use other sensory cues (hearing, olfaction, vision) to direct sharks away from fishing gears have not yet been developed (Jordan et al. 2013).

While the implementation of technical measures to avoid seabird bycatch has already shown a positive impact on seabird populations (Robinson and Jones 2014) and some other measures have reduced interactions with sea turtles (Watson et al. 2005), less progress has been made to reduce the mortality of elasmobranchs. The challenge for the coming years is to find innovative MMs to be implemented with success otherwise enforce one or several management measures presented in Table 3 to reduce shark mortality.

5.2 Recent innovations for tuna purse seine fisheries with more to be done

In the past, modified fishing practices successfully reduced dolphin mortality in the purse seine fishery operating in the eastern Pacific Ocean (Hall et al. 2000). In recent years, breakthroughs and noticeable innovations to reduce the mortality of elasmobranchs (and other bycatch) have emerged in some of these fisheries. These developments have benefitted from purse seine fisheries being well monitored; significant research efforts (including international programmes, such as the ISSF and the EU-funded FP7 project #210496 MADE) were undertaken in collaboration with the fishing industry (Dagorn et al. 2008; Restrepo and Dagorn 2010). Already, established good relationships between fishers, fishing companies and scientists have facilitated the exchange of ideas and acceptance of proposed MMs (Poisson et al. 2014b).

Whilst the incidental capture of elasmobranchs in purse seine fisheries is generally considered low in comparison to other tuna fisheries, it can have a bigger impact on some specific taxa. Murua et al. (2013) estimated that the European purse seine fleet operating in the tropical Indian Ocean contributed approximately 3% to the total silky shark mortality. However, the impact of the entangling DFADs could be significant given the number of units deployed by the various fleets and that the entanglement mortality of silky shark in the Indian Ocean was 5–10 times higher than previous mortality estimates (Filmalter et al. 2013). Recently, much progress has been made in identifying effective MMs to reduce silky shark mortality that could be implemented rapidly in the purse seine fishery. The deployment of non-entangling FADs could reduce the fishery impact on sharks and other bycatch groups (Filmalter et al. 2013). The use of non-entangling FADs has been adopted in both the Indian (IOTC Res 13-08) and in the eastern Pacific Ocean (IATTC C13-04). Finally, the prohibition of setting on whale shark *Rhincodon typus* has recently entered into application in the Pacific and Indian Oceans (WCPFC CMM 12-04, IOTC Res. 13-05, IATTC C13-04).

Application of other MMs discussed in this study may also reduce the mortality on elasmobranchs such as setting on larger tuna aggregations, which can reduce the magnitude of the bycatch while maintaining the same total yield (Dagorn et al. 2013). The use of a hopper, which greatly facilitates the sorting process on the upper deck, could be introduced in the short term (Poisson et al. 2014b); and this would facilitate the release of incidental bycatch. Other MMs that are considered promising, but need further research, include improving the conveyor belt and waste chute system, release panels for sharks and towing the FAD out after encirclement, which could allow sharks to escape.

5.3 Scarcity of information and solutions for bycatch in drift and gillnet fisheries

There is a lack of information on the extent of bycatch and its impact on elasmobranch populations in artisanal drift and gillnet fisheries of developing countries, but it is considered that such fisheries can have a high level of shark bycatch (Rogan and Mackey 2007; MRAG 2012; Ichii et al. 2015). These fisheries are thought to be one of the main causes of elasmobranch bycatch and mortality in the Indian Ocean (Moazzam and Nawaz 2014) and Mediterranean Sea (Tudela et al. 2005; Murua et al. 2013; Baulch et al. 2014). Mortality generally increases with increasing soak time, especially for those species that are obligate ram ventilators (Manire et al. 2001).

Solutions to reduce the mortality of sharks and rays in these fisheries are very limited. Among the possible measures the modification of the mesh slack is considered as the best method but with a limited positive effect. Again, the use of magnets to repel sharks from the gear has shown promise in laboratory experiments, but the transfer to the real world is still difficult to achieve (Rigg et al. 2009).

Resolutions 44/225 and 46/215 adopted in 1989 and 1991 by the United Nations General Assembly, recommended a moratorium on all large-scale pelagic driftnet fishing by June 1992 as they are a threat to vulnerable species. Subsequently, t-RFMOs adopted regulations banning the use of driftnets >2.5 km targeting tuna and tuna-like species (Table 1). Large-scale, high seas driftnet fishing has been banned internationally, and so there is a lack of contemporary data and research on this gear, which may still be used illegally in high seas fisheries and in some national waters (Murua et al. 2013; Moazzam and Nawaz 2014). More robust enforcement of this prohibition is required in some areas and t-RFMOs could usefully develop improved schemes to report IUU fishing.

5.4 Appropriate fishing practices reduce bycatch in recreational fisheries

Recreational fisheries targeting sharks can contribute to the global shark mortality in some areas (Heberer et al. 2010), with the degree of total mortality related to angling practices. Competition fishing (including shark derbies), trophy hunting, long fight times, caudal-based angling techniques (i.e. trolling for thresher sharks) and poor handling techniques can increase the mortality associated with recreational fishing. Whilst "Catch and release" is practiced more widely nowadays, anglers could benefit from more guidance to ensure that they adopt good handling and release practices. Complementary studies are also needed to make sure that catch and release recreational fisheries are not causing a significant degree of mortality to the stocks in question. It is worth noting that angler education programmes that have tried to promote voluntary changes in angler behavior have shown promise in some inland fisheries (Cooke et al. 2014). The studies presented in this review showed that when fishing and handling techniques are performed properly, released sharks had a high survivorship. This confirms that some fishing techniques should be definitively banned.

5.5 Special consideration for improved handling practices, fisher training and fleet communication programmes

Several studies have highlighted the fact that handling practices is a key factor which can increase the survival of discarded fish (Campana et al. 2009; Abascal et al. 2011; Poisson et al. 2014a). Dissemination of good handling and release practices and appropriate equipment have been identified as good methods to reduce mortality and injury of vulnerable species (Campana et al. 2009; Abascal et al. 2011; Gilman et al. 2014; Poisson et al. 2014a).

These measures would likely be accepted by the industry as the implementation costs would be low compared to other options. Some good practice standards using visual aids to make the information more accessible already exist and could be adopted for other fisheries, but complementary procedures should be developed in collaboration with fishers and experienced observers.

The success of such measures would also benefit from more effective communication campaigns, including education programmes, post-implementation monitoring and longstanding collaboration in order to transfer the mitigation methods to the wider fleet (Poisson et al. 2012, 2014a). Contracting Parties of t-RFMOs (members and cooperating countries) should encourage "the release of live sharks, especially juveniles and pregnant sharks" (IOTC Res. 05-05) but no guidelines are currently provided to fishers to help increase postrelease survival. Safe and effective handling techniques should be developed with fishers and incorporated as a routine task during fishing operations. The implementation of safe and effective handling techniques should aim to increase the safety of the crew, prevent wasting time and reduce gear loss/damage.

Training workshops can increase fishers' knowledge on bycatch issues, improve their ability to remain alert and increase their acceptance of guidelines and proposed MMs. This may also benefit other taxonomic groups, as the goal is to change the attitude of fishers in relation to bycatch in general. The fishing industry will likely be supportive of any improvement in handling practices, especially if they are safe and not time-consuming, and if any dedicated tools needed are provided. For example, since January 2007, some shark and swordfish permit holders in the USA are required to attend a "Protected Species Safe Handling, Release, and Identification Workshop"; and all federally permitted shark dealers are required to attend shark identification workshops. These workshops are designed to educate the fishing industry on the best techniques for safe handling and release of entangled and/or hooked protected species, and to improve species identification in relation to reporting catches and identifying protected species. Such education programmes could usefully be considered in other regions, including by t-RFMOs.

Worldwide, fisher communities have adopted voluntarily their own communication network to address problematic interactions. Whilst it is easy for such a MM to be established by the fishing industry, improved monitoring systems could facilitate the near real-time reporting of observations.

5.6 Paucity of studies on post release survival rates

Survivorship of live animals returned to the sea after being captured is often unknown, and a proportion of the sharks that are released alive could die in the short-term, due to injuries, sustained stress or increased susceptibility to predation. The elapsed time between the capture and the hauling could also influence the postrelease mortality. Using hook timers, Poisson et al. (2010) showed that blue shark and oceanic whitetip shark exhibited long survival times of up to 14 h after capture.

Hence there is a need to better estimate PRS. Ranking sharks according to their susceptibility is a useful exercise to help prioritizing management decisions for vulnerable species, including identifying where MMs, other regulation or special protection may be warranted. Special attention should be given to species showing high level of at-vessel mortality. In such cases, to improve gear selectivity (i.e. to reduce the chances of capture) is required. In contrast, if a species is deemed hardy and has a high chance of survival, then measures to improve handling and release may be the only requirement to minimize incidental mortality.

Whilst many studies have provided estimates of at-vessel mortality, based on large sample sizes collected during observer programmes, these values will often underestimate total capture mortality. Accurate species-specific and fishery-specific estimates of both at-vessel and postrelease mortality rates are required for the effective estimation of bycatch mortality, which can inform both stock assessments and help identifying effective management options. Although there are a large number of publications on tag-and-release mortality for various fish species, there is a lack of information about PRS (Worm et al. 2013), for few elasmobranch species taken in commercial fishing operations (including blue shark, silky shark and the spinetail devil ray). For the quantification of commercial discard mortality, it is crucial that robust experimental protocols are used and appropriate recovery periods are monitored. The results should not be based only on healthy individuals, which could bias the results, but on either a random selection of captured sharks, regardless of their vitality, or on a defined sample sizes per health category (Campana et al. 2009; Poisson et al. 2014a).

The assessment of mortality should help identifying species at greatest risk due to the pressure of commercial fishing and understand how PRS can be increased by changing fishing techniques or fisher behavior, and developing more effective methods of engaging fishers in the management and conservation of elasmobranchs. With regard to the direct benefits of the studies on mortalities estimates, some authors proposed to incorporate dead discard estimates into t-RFMOs shark assessments (Campana et al. 2009; Coelho et al. 2012a; Poisson et al. 2014a).

In addition to carrying out studies for estimating PRS, several authors have argued that technical mitigation measures should be implemented to increase PRS. Musyl et al. (2009) considered that "catch-and-release" practice could be beneficial for mature shark populations and should be considered as a tRFMO management measure. Hutchinson et al. (2015), Coelho et al. (2012), Beerkircher et al. (2002) and Coelho et al. (2013) underlined that such "no retention" policies must be assessed at a species-specific and fisheries level. Some authors supported the idea of promoting and implementing handling practices on-board (Thorpe and Frierson 2009; Poisson et al. 2010, 2014a). Other authors opened the debate about modifications in gear configuration or fishing strategy. Based on their results Carruthers et al. (2009) proposed a complete shift from J-hooks to circle hooks in the swordfish and tuna NW Atlantic Longline fisheries to reduce mortality of blue shark and shortfin mako sharks, and to reduce severe injuries to sharks without decreasing incidence of bycatch. Afonso et al. (2011) noted that circle hooks could reduce gut hookings in sharks caught in SW Atlantic Ocean fisheries, but increased the CPUE for silky and blue sharks. The ban of chemical light sticks could reduce sharks CPUE (Poisson et al. 2010). Promotion of the use of adapted tools such as hooper on-board purse seine could facilitate sharks' release (Poisson et al. 2014b).

Although the reduction of the soak time could increase PRS (Diaz and Serafy 2005; Moyes et al. 2006; Carruthers et al. 2009; Poisson et al. 2010), it could also result in economic losses for fishers. The finning ban alone (Walsh et al. 2009) in the Pacific Ocean or in combination with measures aiming at reducing catch rates ("restrictions on the use of wire leaders", "shark baits" and "shark lines") with measures that could increase the discard rate and the postrelease survival rate ("finning bans") could be the most effective to reduce the impacts on sharks. Finally, in some areas, a seasonal closure of fishing area to protect juvenile swordfish may be beneficial to sharks population (Beerkircher et al. 2002).

5.7 Development of specifically designed equipment in collaboration with industry

Practical solutions to reduce elasmobranch mortality should be achieved by a close collaboration among various disciplines, including gear technologists, companies developing fishing gears, engineers (boat design), fishers (both skippers and crews), fishery scientists and biologists.

In the case of longline gears, as the interactions are difficult to avoid, it is important to work on the selectivity of the hook, to avoid its ingestion, and to make it corrodible in a short term. Most of the studies conducted using circle hooks have shown that improved hook designs can reduce hooking mortality by minimizing deep hooking (e.g. gut hooking) and bleeding, thereby allowing more animals to be released with non-lethal injuries. In this sense, scientists undertaking experimental fishing trials to determine the feasibility and effectiveness of appropriate hooks should consider involving manufacturers rather than blindly using the conclusions of studies performed elsewhere, which may be not applicable to the particular fishery.

It has been shown that some fishers want to retrieve the terminal tackle (Gilman 2011), so it is important to make them cheap or to develop appropriate tools to recover the hooks without causing serious injuries to the sharks. Carruther and Neis (2011) reported innovative uses of turtle de-hooking gears by skippers when releasing other bycatch species. It is very important to provide good tools, like suitable hook removers, with the appropriate training to demonstrate their effectiveness; because some fishers perceive such tools to be impractical, time consuming or potentially dangerous to use with sharks. The development of effective hook removal systems can help fishers addressing some of the MMs implemented by t-RFMOs.

Some modifications of equipment on-board fishing vessels cannot be achieved without collaboration among fishers, engineers and experts in fishing technology. In the case of purse seiners, some principles and guidelines for further improvements (e.g. use of a hopper, improved conveyor belt and waste chute system) have been suggested (Poisson et al. 2014b).

Lastly it is important to develop and support any chosen MM in collaboration with the fishing industry, as this will facilitate successful implementation. This could be done using incentives that encourage fishers to develop and/or adopt innovative solutions.

5.8 Studies on elasmobranch behavior to understand potential interactions with fisheries

The development of electronic satellite-linked archival and telemetric tags allowed researchers to better understand vertical and horizontal movements and migratory patterns of various elasmobranchs species. The improved knowledge of such behavior and habitat utilization over one or two-year cycles is essential for (1) predicting the risk of interaction of sharks with fishing fleets and gears (Stevens et al. 2010) and other shark-human interactions (Kneebone et al. 2013), (2) assessing the potential efficacy of any proposed Marine Protected Area (MPAs) for large predators (Queiroz et al. 2012), (3) providing information to better understand the life history stages (Domeier and Nasby-Lucas 2013) and site fidelity (Werry et al. 2014), (4) and understanding how and why MM can be effective for different species, sizes, sexes and life stages.

5.9 Sharks management in t-RFMOs

There is evidence of progress at the international level with regards to the number of recommendations and resolutions for shark conservation which have increased in the last decade. T-RFMOs have achieved progress in adopting binding measures for sharks' conservation which are consistent across the t-RFMOs. Moreover, most of the decisions adopted are binding. However, there is neither enforcement nor penalty when Contracting Parties do not follow the t-RFMOs mandatory regulations which can give the impression that shark issues are still of minimal interest for t-RFMOs (Campana et al. 2016).

Catches and discards statistics are still likely to be unrealistic and underreported. As a result, despite the t-RFMO efforts, outcomes from sharks' stock assessment remain highly uncertain and it is difficult to provide the best management advice.

6 Conclusions

This paper provides (1) up to date information and technical specifications on technical MMs, and suggestions for practical options that could be implemented rapidly and in the longer term for the four main gear types used in tuna fisheries, and (2) suggestions for directed future research efforts on MMs. The outcomes of this study are based on the information derived from a broad literature review and from expert judgment. The study focused on technical MMs relating to gear specifications, fishing strategies, and handling practices designed to reduce bycatch and mortality of elasmobranchs, whilst also considering their impacts on other taxonomic groups.

Several resolutions have been adopted by t-RFMOs in recent years to mitigate the impact of tuna fisheries on shark population, including the use of non-entangling FADs by purse seine fleets and avoiding the use of wire traces in longline fisheries. However, the implementation and efficiency of some of those resolutions has not yet been investigated and, therefore, there is not much information available regarding actual benefits to elasmobranch populations. Thus, it is necessary to further study the implementation, efficiency and control of those measures, and to develop further measures to assure avoiding unwanted mortality caused by fisheries targeting tuna resources.

Whilst substantial progress has been made in reducing bycatch of sea turtles, seabirds, and marine mammals in various fisheries, including through physical modifications to the fishing gear or fishing techniques, there have been limited improvements with regards to sharks. The number of potential and efficient MMs which could be implemented at the present time remains somewhat limited.

In conclusion, no single MM method can effectively reduce the mortality of elasmobranchs for all gears. Therefore, the combination of several MMs, as well as cooperative research among stakeholders (scientists, fishing industry, gear technologists and manufacturers) involved in tuna fisheries is considered key to ensuring that levels of dead bycatch and landings are at sustainable levels.

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Online Material

Table S1. Review of the information on at-vessel and postrelease survival (PRS) estimated on-board pelagic and bottom longliners, purse seiners and on vessels using driftnets or gillnets and on recreational vessels in various areas: fishery, location and origin of the data; objectives of the study; details on the fishing gear; results on at-vessel/overall mortality per species; post release survival rate (PRS); Mitigation measure proposed or Management implication; the main results of the study; references.

Fishery /data	Objectives of the study	Gear type and characteristics	At-vessel/overall mortality	Post-release survival (PRS)	Mitigation measure proposed Management implication	other results	Source
Pelagic longlines							
Canadian pelagic longline swordfish fishery in the NW Atlantic Ocean. Data collected by fisheries observers 513 longline sets	Study focusing on blue sharks (*Prionace glauca*) (1) to estimate at-vessel mortality and post-release mortality (3) to explore the possibility of using this information during assessment of the North Atlantic blue shark stock.	Mostly Circle hooks (size 16/0) but also J-hooks and offset J-hooks, either 8/0 or 9/0	12-13% /35%	81% (40 PSATs deployed)	• Proposition to incorporate dead discard estimates into ICCAT shark assessments.	• The probabilities of hooking mortality decrease with increasing specimen sizes • 95% of the post-release mortality occurred within 11 days after their release • Sharks are likely to recover within a period of 2to 7 days after their release • Sharks observed in healthy condition at-haulback show high survivorship rates	(Campana *et al.*, 2009)
Commercial longline targeting swordfish and/or tuna NW Atlantic Ocean Data collected by fisheries observers 859 longline sets	Study focusing on the main species bycaught (1) to estimate bycatch species (by size classes) likely to survive after release; (2) to investigate the impact of the hook type, soak time and animal length on the odds of by-catch survival (3) to propose solution to reduce the by-catch mortality	Mostly Circle hooks (size 16/0) but also J-hooks and offset J-hooks, either 8/0 or 9/0	For Pelagic stingray (*Pteroplatytrygon violacea),* "J" hook: 10%; circle hook: 2% / No overall mortality	none	• Switching from J-hooks to circle hooks seems to increase at-vessel survival rate and to decrease post-release mortality for blue shark and shortfin mako (*Isurus oxyrinchus*). • Make mandatory a complete shift to circle hook could have a positive impact on survival rate and on the severity of the injuries especially in the swordfish fisheries but definitively would not decrease incidence of by-	• Over 90% of blue shark were released alive • Odds of severe hooking injuries caught on circle hooks are likely to decrease for porbeagle (*Lamna nasus*), shortfin mako and blue shark	(Carruthers *et al.*, 2009)

					catch • The probabilities of hooking mortality increase for swordfish, yellowfin tuna and longnose lancetfish (*Alepisaurus ferox*) with increasing soak times, however it is important also to consider that catch increase with longer soak times.	
Research cruise pelagic longline fishery SW Atlantic Pelagic longlining experiment 12 longline sets; 7,800 hooks	Investigation of the effects of fishing gear modifications (hook type : circle *vs* J - hook and position of the hook in the water column : pelagic *vs* bottom longlines) on catch rates and mortality of elasmobranch species	18/0 circle hooks and 9/0 J-hooks	Night shark (*Carcharhinus signatus*), 100% for both hook types; Blue shark, 27.2% for circle hooks; 70% for J-hooks; Silky shark (*Carcharhinus falciformis*), 22.2% for circle hooks and 80% for J-hooks; whitetip shark (*Carcharhinus longimanus*), 22.2% for circle hooks and 66.5% for J-hooks; whitetip shark, 22.2% for circle hooks and 66.5% for J-hooks; dusky shark (*Carcharhinus obscurus*.), 28.5% for circle hooks and 100% for J-hooks; tiger shark (*Galeocerdo cuvier*), 16% for circle hooks and 50% for J-hooks; mako shark, 20% for	none	• The use of circle hooks (size 18/0, 0 offset) for both fishing gears could reduce the mortality at-haulback of most species caught in both fisheries. It could also reduce internal lodging hooks. • The CPUE of silky and blue sharks are higher with circle hooks.	(Afonso *et al.*, 2011)

			circle hooks and 100% for J-hooks; scalloped hammerhead (*Sphyrna lewini*), 33.3% for circle hooks and 87.5% for J-hooks/ No overall mortality				
Research cruise pelagic longline fishery targeting Swordfish and tunas SW Atlantic Pelagic longlining experiment 17 longline sets ; 17,000 hooks	Investigation of the effects of fishing gear modifications : hook type (circle *vs* J-hook) and leader material (nylon *vs* wire) on longline catch and on mortality rates of target and by-catch species	Circle hooks size 17/0 (10 offset) and J-hooks size 10/0 (10 offset)	regardless the hook type Blue shark, 31%; tiger shark 67%; Silky shark 75%; Whitetip shark 82%; Pelagic Stingray 5%; Shortfin Mako 75%; Alopidae 89%; Hammerhead shark 100% / No overall mortality	none:	• The use of monofilament leaders could induce higher catch and mortality rates than expected • Nylon leaders are more effective at catching target species		(Afonso *et al.*, 2012)
Portuguese pelagic longline swordfish fishery in the Atlantic Ocean 762 longline sets; 1,005,486 hooks	Study focusing on blue sharks (*Prionace glauca*) (1) to predict at-vessel mortality; (2) to investigate the impact of several variables (year, specimen size, fishing location, sex, season and branch line material) on the mortality rate	Stainless steel J-hooks baited either with squid (*Illex spp*.) or mackerel (*Scomber spp*.) setting at 17:00 Hauling time at 06:00 and fishing at 20-50m depth	Blue shark 13.3% no overall mortality	none	• Proposition to consider the prediction of blue shark at-vessel mortality by fisheries management organizations during (Coelho *et al.*, 2012)ment analysis. Knowing that larger size had increased probability of surviving it could be used to determine the efficiency of a regulation of blue shark landing sizes		(Coelho *et al.*, 2013)
Commercial longliners targeting swordfish in the Atlantic Ocean: Data collected by fisheries observers 834 longline sets; 1,078,200 hooks	Study aiming at (1) estimating at-vessel mortality for 15 species ; (2) investigating the impact of several variables (sex, specimen sizes and fishing area) on the mortality rate	Steel J-style hooks, squid (*Illex spp*.) or mackerel (*Scomber spp*.) for bait	Blue shark, 14.3%; Crocodile shark (*Pseudocarcharias kamoharai*),13.3% Shortfin mako, 35.6%; Bigeye thresher (*Alopias superciliosus*), 50.6%; Pelagic stingray :,1%; Smooth hammerhead ,71%; Silky shark, 55.8%;	none	• Proposition to incorporate the information collected into further stock assessment models, including ecological risk assessment analysis • Discarding practices must be assessed at a species-specific level.	• Blue shark and shortfin mako of larger size had increased probability of surviving	(Coelho *et al.*, 2012)

		Oceanic whitetip, 34.2%; Longfin mako (*Isurus paucus*), 30.7%; Mantas & devil rays, 1.4%; Tiger shark, 2.9%; Tope shark(*Galeorhinus galeus*), 0%; Scalloped hammerhead, 57.1%; Eagle rays, 0%; Bignose shark (*Carcharhinus altimus*), 60%; Porbeagle(*Lamna nasus)*, 30%; Common Thresher (*Alopias vulpinus*), 66.7%; Great hammerhead (*Sphyrna mokarran*), 0%/ no overall mortality				
Tuna longline vessels fishing in the Republic of the Marshall Islands Observers data port sampling and logbook data Data collected by fisheries observers 1,499 longline sets	Study aiming at (1) assessing the fishery interactions with sharks; (2), identifying potential shark targeting methods; and (3) investigating environmental and fishing method factors which could affect shark catch rates.	Bigeye thresher shark (*Alopias superciliosus*), 50%; Common thresher shark (*Alopias vulpinus*), 52.9%; Pelagic thresher shark (*Alopias pelagicus*), 63.8%; Copper shark (s.n *Carcharhinus brachyurus*), 5.6%; Silvertip shark (*Carcharhinus albimarginatus*),15%; blue shark, 19.6%; silky shark, 26.5%; white tip shark, 30.6% blacktip shark, 60.0% pelagic stingray, 18.5%; shortfin mako, 50.3%; longfin mako (*Isurus*	none	• Five measures are explored namely "Time and area options", "Finning ban", "No retention", "Gear and method restrictions" and "Combined measures"; the most effective would be to combine measures aiming at reducing the catch rate (" restrictions on the use of wire leaders", "shark baits" and "shark lines") with	• the lack of studies on species specific post-release mortality prevent currently the assessment of the effectiveness of a combined measures	(Bromhead *et al.*, 2012)

			paucus), 53.6%; scalloped hammer head, 75%; Crocodile shark, 38.7%/ no overall mortality		measures that could increase increase the discard rate and the post-release survival rate (“finning bans”)		
Réunion Island based commercial longliners targeting Swordfish in the South West of the Indian Ocean Pelagic longlining experiment onboard commercial vessels 160 sets; 28,974 hook timers deployed	investigation on (1) the effects of fishing gear characteristics and environmental parameters on the catch composition and catch rates and (2) estimates of the at- vessel mortality rates for large pelagic fish	steel J-style hooks J hooks (size 8/0 or 9/0) , squid (*Illex spp.)* for bait	blue shark,51%; oceanic whitetip,59% no overall mortality blue shark and oceanic whitetip shark exhibited long survival times of up to 14 hours after capture	none	• Reducing the soaking period would increase the number of sharks released alive. • Catch-and-release measure in longline fisheries can be a viable management tool to reduce shark mortality • Banning the use of chemical lightsticks which are suspected to attract sea turtles and sharks in the vicinity of longlines and to constitute a potential toxicant to marine flora and fauna.		(Poisson *et al.*, 2010)
Commercial swordfish, and tuna, pelagic longline fleet off the Southeastern United States Data collected by fisheries observers 961 sets	investigation on sharks by-catch in the pelagic fisheries: estimates of the magnitude of shark by-catch, distribution, relative abundance, and characteristics of shark populations	7/0–11/0 size hooks depth varying from shallow sets: 35 to 60 m Night set: fishing gear setting around sunset and haulback around dawn, use of chemical light sticks attached near the hooks, mackerel or squid for bait	:Silky shark, 66.3%; Dusky shark, 48.7%; Night shark, 80.8%; Blue shark, 12.2%; Tiger shark, 3%; Scalloped hammerhead, 61%; Oceanic white tip, 27.5%; Rays,0%; Sandbar shark, 26.8%; Bigeye thresher, 53.7%; shortfin mako,35%/ no overall mortality	none	• by-catch mortality is not prevented by retention prohibitions • The seasonal closure of fishing area to protect juvenile swordfish may have been beneficial to sharks population	• Sharks using the pelagic habitat off the southeastern United States vary greatly depending on the species, year, and season.	(Beerkircher *et al.*, 2002)
Commercial longliners targeting	investigation on the effects of some	Not specified	Blue shark: 31%	none	• Shorter longline set duration would likely	• Blue shark of larger size had increased probability	(Diaz and Serafy, 2005)

either Swordfish or Swordfish and tuna in the Atlantic Ocean Data collected by fisheries observers 702 sets	possible explanatory variables (fish size, set duration, water temperature) on the at-vessel mortality rate		no overall mortality		lead to negative economic impacts therefore industry would not be supportive of this measure	of surviving • The proportion of live releases is likely to decrease with duration of set	
Research cruise targeting swordfish in the Pacific Ocean	Study aiming at (1) estimating at-vessel mortality rates for 7 shark species and Post –release mortality for 5 shark species; (2) investigating vertical and horizontal movement patterns	16/0 and 18/0 ; circle hooks ; no offset ; pacific saury for bait and soaking time: 10-24h	Blue shark, 5.9%; Crocodile shark, 66.7%; Oceanic whitetip,5.3%; Shortfin mako, 0%; Silky shark,11%; Bigeye thresher shark,25%; Pelagic thresher shark,35.7% no overall mortality	Blue shark, 85% (16 PSATs deployed)	• Catch-and-release is beneficial for mature biomass in shark populations and should be considered as a viable management in longline fisheries • A better knowledge of the temporal and spatial vertical distribution patterns could lead to identification of more efficient management strategies	• three broad groups of Pelagic species based on daytime temperature preferences have been identified : 1) epipelagic species (silky and oceanic whitetip sharks), 2) meso-pelagic-I species (blue shark and shortfin mako, 3) mesopelagic-II species (bigeye threshers),	(Musyl *et al.*, 2011)
Experimental drift longline in the Pacific Ocean 93 sets	Study aiming at investigating the effects of rod-and-reel and longline fishing process on plasma catecholamine levels, blood haematocrit and plasma lactate in mako, thresher and blue sharks.	2/0 size and 12/0 size 'J' hooks baited with mackerel or squid longline was deployed for a short period (around 3 h) before recovery	Blue shark, 6%; Shortfin Mako shark, 10%; Common thresher shark (*Alopias vulpinus*), 5%/ No overall mortality	Shortfin Mako: conservative estimate of 80% viability on the sharks released	None		(Hight *et al.*, 2007)
Experimental longline fishing strategy approximated the typical Hawaiian ''swordfish'' style of fishing employed by commercial longliners in the	Study focusing on blue sharks (*Prionace glauca*) to predict the post-release survival of based on electronic tagging and biochemical analysis	15/0 circle hooks baited with squid (*Illex spp.*).	5%	blue shark, 100% (23 PSATs deployed) estimated with 11 pop up tags that reported data (12 tags failed at reporting data): PRS 95% based on	• Shorter soaking period would likely lead to increase the number of sharks released alive • predictive information on post-release survival should help in identifying management measures	• Sharks observed in healthy condition at-haulback likely to survive long term when released • the cooler water temperature would reduce locomotor activities and may increase the likelihood of survival	(Moyes *et al.*, 2006)

Pacific Ocean.				biochemical analyses			
Commercial longliners targeting Swordfish or Swordfish and tuna in the Pacific Ocean Data collected by fisheries observers 53,014 sets	Assess the progress by the longline fishery in reducing shark mortality	Not specified	Blue shark: Deep set: 4% shallow set: 6%/ No overall mortality	none	• The finning ban lead to dramatic decrease in the mortality estimates • The closure of the shallow-set can decrease shark catches		(Walsh *et al.*, 2009)
Commercial longliners targeting tuna in the Pacific Ocean Data collected by fisheries observers	investigation on sharks by-catch in the pelagic fisheries	Not specified	Blue shark: 13% No overall mortality	none		• immature males and females were predominant	(Francis *et al.*, 2001)
Commercial longliners targeting bigeye tuna in the Pacific Ocean 16 sets; 14,410 hooks	Study aiming at describing the depth distributions and capture times of pelagic fishes	J hooks (size 8/0 or 9/0) baited with saury *Cololabis saira* soaking time: 12 h	Blue shark: 0% Whitetip shark : 15% Thresher shark : 40% No overall mortality	none	• Improving the knowledge on specific habitats of pelagic species could assist in efficient changes in the fishing methods to reduce by-catch	• whitetip and blue sharks were mostly caught in depth ranging from the surface to 100m	(Boggs, 1992)
Tropical tuna purse seine							
commercial fishing trips and one chartered research cruise in the Indian Ocean	Study focusing on silky sharks to estimate the at-vessel mortality , post release survival rate and overall mortality	Purse seine set around FADs	Silky shark: 69%/ 81%	31 PSATs deployed PRS rate : 52%	• Promote good handling practices to avoid injuries to the crew when handling sharks and rays and minimize physical trauma and stress of animals in order to improve their post-release survival. • the use of a hopper is recommended as it facilitates the sorting of fish on the upper deck and even suggest redesigning it to improve the retention of small	• The high level of at-vessel mortality illustrates the importance of identifying methods that prevent sharks from ending up in the sack at the end of the hauling process • While the mortality rates reported in this study appeared to be high, it is worth noting that the contribution of the purse seine fishery to total pelagic shark mortality in the Indian Ocean is	(Poisson *et al.*, 2014)

					sharks on the upper deck (vs lower deck) and facilitate their quick release at sea • New information on the impacts of this fishery on pelagic elasmobranches which can now be incorporated into further stock assessment models, including ecological risk assessment analysis.	believed to be extremely small.	
commercial fishing trips and one chartered research cruise in the Indian Ocean	Study focusing on silky sharks to estimate the at-vessel mortality , post release survival rate and overall mortality using a combination of electronic tagging and blood chemistry analysis	Purse seine set around FADs	Silky shark 60%/ 84%	15.83% (28 PSATs deployed) individuals entangled in the net 68.7%; sharks that came up in the first brail, 16.7%	• The "no retention" policy for purse seine fisheries as a management tool would not be effective • complementary studies on post-release mortality for other gears impacting this species is needed to improve stock assessment and population level management	• More research is required to develop innovative solutions to reduce fishing gear interaction (encirclement) and release sharks while they are still free swimming in the net	(Hutchinson *et al.*, 2015)
commercial fishing vessel in the Eastern Pacific Ocean	Study aiming at investigate the total mortality of pelagic sharks	Purse seine set around FADs	Silky shark: overall at-vessel mortality rate was 59% Total mortality rate ranged from 80% to 95%. scalloped hammerhead at-vessel mortality 0%	28% (n=13) 0%			(Eddy *et al.*, 2016)
commercial fishing trips skipjack tuna (*Katsuwonus pelamis*) purse seine fishery	Study focusing on spinetail devilrays (*Mobula japanica*) (1) to assess the post-released mortality ; (2) to describe their spatial and vertical behaviour			75% (6 PSATs deployed) Only four of the six tags reported data, and three of the four rays that provided data died within 2–4	• An implementation of the handling practices provided by the author could be beneficial for the species		(Francis, 2014)

				days of release			
Gillnets							
Experimental fishing focused on two commercial fisheries, Spanish mackerel (*Scomberomorus maculatus*) and spot (*Leiostomus xanthurus*).	Study investigating gillnet selectivity and assessing by-catch mitigation;	Gillnet mesh sizes were 7.2 cm (spot fishery) and 7.6 and 10.2cm (Spanish mackerel fishery). All nets were monofilament nylon hanging coefficient E = 0.50 Experimental fishing was conducted in coastal waters (0–5 km)	The mean capture mortality rate for Atlantic sharpnose sharks (*Rhizoprionodon terraenovae*) (80.4%), bonnethead sharks (*Sphyrna tiburo.*) (71.5%), blacknose sharks (*Carcharhinus acronotus.*) (81.3%) and blacktip sharks *Carcharhinus limbatus*) (90.5%) was high irrespective of mesh size or primary entanglement modes. overall shark mortality rate of 78.6%.		• The modification of the gear (gillnet tension, float size and lead-core lead-line weight) lead to a reduction of the incidental capture of sharks • sharks released in a good condition and likely to survive the fishing gear interaction	• As catch rates for some shark species were lower, the modified gear reduced the damages to the net caused by sharks	(Thorpe and Frierson, 2009)
Scientific experiments anchored gill nets in inshore waters NW Atlantic (South-west Florida)	Study primarily looking at determining the serological changes in sharks following gillnet capture process	11.75–15.25 mm stretched mesh size; 45–60 min. soak time; depth <3 m	blacktip shark 24.2% bull shark :18.5% Bonnethead shark : 30.8%				(Manire *et al.*, 2001)
Scientific gillnet experiments NW Atlantic (Gulf of Mexico)	Study aiming at quantify the by-catch mortality of small sharks based on tagging data	monofilament gillnets with a stretch mesh of 11.4 cm, height 3 m, length ~ 366 m, soaking times ~1 h	blacktip shark 40% /overall mortality: 58% Bonnethead shark : 30.8%/ overall mortality: 62%	69% of blacktip sharks and 60% of Bonnethead sharks survived the stress of gillnet capture			(Hueter *et al.*, 2006)
Rod and reel							
California recreational fishery that typically captures individuals by hooking them in	Study primarily looking (1) at post-release survivorship of common thresher sharks estimating (2) at the serological changes in	Lead-headed lures rigged with tandem 8/0 Mustad 7691 J-hooks, baited with chub mackerel		19 PSAT (10-day deployments) PRS rate estimated at 74 % All mortalities	• The caudal-based capture methods used in this recreational fishery may not be suitable for an effective catch-and-release based		(Heberer *et al.*, 2010)

the caudal fin	sharks following angling capture process		occurred in large individuals (180cm FL) with fight times 85 min	conservation strategy	
southern California recreational fishery	Study focusing on common thresher sharks to compare post-release survivorship for shark (1) captured with caudal-based angling techniques and released with trailing gear left embedded and (2) sharks captured and released using mouth-based angling techniques.	Trailing gear: 0.5 kg lead-headed trolling lures pre-rigged with wire leaders (length ~2 m) and tandem 8/0 J hooks baited with chub mackerel. Mouth-based experiments: Fishing tackle consisted of 8/0–10/0 non-offset circle hooks (EagleClaw L2004, USA) with 2 m of 50 kg monofilament leader material.	10 PSATs were deployed ((10-day deployments) Overall PRS rate estimated at 22 % with the trailing gear. estimated with 9 tags (1 tag failed at reporting data): 7 PSATs (10-day pop-off schedule) PRS rate for the mouth-hooking was 100%	• The trailing gear techniques appears detrimental affecting negatively post-release survival, the mouth-based angling techniques are likely to result in high survivorship	(Sepulveda *et al.*, 2015)

Table S2a. Mitigation options and ranking against criteria for longlines (SWO swordfish longline; TUN tuna longline; SHK shark longline).

* Seabirds, sea turtles and marine mammals

2	Very positive
1	Positive
0	No effect or not applicable
-1	Negative
-2	Very negative

Mitigation categories

- Fishing gear modification
- Fishing practices and strategy
- Practices to increase survival rates after release

Longlines	Reduce interaction	Minimize discards	Facilitate escape	Improve survivorship	Other bycatch*	Environmental impact	Carbone footprint	Total Score 1		Target species Impact	Technical feasibility to detect a response	Additional Cost of implementation	Implementation feasability	Impact on current data collected	crew safety	Industry support	Total Score 2	Grand Total
	Biological and Environmental impact									**Fisheries impact and control**								
Prohibition of light attractors	2	2			2	2		8	SWO	-2	2	2	2			-2	2	10
	2	2			2	2		8	TUN		2	2	2			2	8	16
	2	2			2	2		8	SHK	-2	2	2	2			2	6	14
Prohibition of wire leaders		2	2	2	2			8	SWO	2	2	2	2	-1	2	2	11	19
		2	2	2	2			8	TUN	2	2	2	2	-1	2	2	11	19
		2	2	2	2			8	SHK	-2	2	2	2	-1	2	-2	3	11
Circle hooks			1	2	2			5	SWO	1	2		2			1	6	11
			1	2	2			5	TUN	1	2		2			1	6	11
			1	2	2			5	SHK	1	2		2			1	6	11
Corrodible hook				2	2			4	LL		2	1	2			2	7	11
Weak hook		2	2	2	2			8	LL	1	2		2	-1	1	2	7	15
Increase in hook size			2		2			4	LL	1	1		2			2	6	10
Artificial bait	2	2			2	2		8	SWO	2	2	1	1		2	1	9	17
	2	2			2	2		8	TUN	2	2	1	1		2	1	9	17
	2	2			2	2		8	SHK	2	2	1	1		2	1	9	17
Fish not squid bait	1				2			3	SWO	-2	2	2	2			-2	2	5
	1				2			3	TUN	2	2	2	2			2	10	13
	1				2			3	SHK	1	2	2	2			-2	5	8
Magnetic, E+ metals, electrical deterent	1	1						2	LL	2	2	-1	-1		2	1	5	7
Olfactive repellent	2	2						4	LL	2	2	-1	-1		2	1	5	9
Auditory deterrent and attractors	2	2						4	LL	2	2	-1	-1		2	1	5	9
Fleet communication	2	2			2			6	LL			2	2		2	2	8	14
Reduction of soak time	2	2		2	2		-1	7	LL	-1	1	1	1			1	3	10
Prohibition of the use of live bait	2				2			4	LL	1		2	2			2	7	11
Deep setting	1	2			2			5	SWO	-2	2	2	2			-2	2	7
	1	2			2			5	TUN	2	2	2	2			1	9	14
	1	2			2			5	SHK	-2	2	2	2			-2	2	7
Management of offal and spend discharge	2	2			2			6	LL				2		2	2	6	12
Topographic and oceanic features	2	2			2		-1	5	LL	2	-1	-1	2		2	1	5	10
Enforcement of safe handling and release				2	2			4	LL		2		2	2	2	2	10	14
Workshop/training				2	2			4	LL		2	-1	2	2	2	2	9	13
Mandatory seaTurtle/sharks safe handling equipment				2	2			4	LL		2	-1	2	2	2	2	9	13

Table S2b. Mitigation options and ranking against criteria for tropical purse seine.

	Biological and Environmental impact								Fisheries impact and control								
Tropical Purse seine	Reduce interaction	Minimize discards	Facilitate escape	Improve survivorship	Other bycatch*	Environmental impact	Carbone footprint	Total Score 1	Target species Impact	Technical feasibility to detect a response	Additional Cost of implementation	Implementation feasability	Impact on current data collected	crew safety	Industry support	Total Score 2	Grand Total
Prohibition of Entangling DFADs	2	2	2		2	2	2	12		2	-1	2			2	5	17
Mandatory Use of hopper				2	2			4		2	1	2	2	2	2	11	15
Release panel for sharks	2	2	2		2			8	1	1	-2	-2		2	2	2	10
Improvment of the conveyor belt and waste chute			2	2	2			6		2	-1	2		2	2	7	13
Setting on bigger aggregations	2	2			2		-1	5	1	2		2			1	6	11
DFAD monitoring and management plan	2	2			2		-1	5	-2	2	-1	2			-1	0	5
Ban of supply vessel	2	2			2	2	UK	8	-2	2		2			-1	1	9
Towing FAD after encirclement	2	2	2		2			8	1	1		-1		2	1	4	12
Multiple FADs	2	2	2		2			8		1		-1		2	1	3	11
Use Bait station	2	2	2		2			8		1	-1	-1			-1	-2	6
Restriction of setting on whale sharks and marine mammals	2	2			2			6	2			2		2	1	7	13
Enforcement of safe handling and release				2	2			4		2	2	2	2	2	2	12	16
Workshop and training				2	2			4		2	-1	2	2	2	2	9	13

Table S2c. Mitigation options and ranking against criteria for driftnet and gillnet.

	Biological and Environmental impact								Fisheries impact and control								
Gill/drift nets	Reduce interaction	Minimize discards	Facilitate escape	Improve survivorship	Other bycatch*	Environmental impact	Carbone footprint	Total Score 1	Target species Impact	Technical feasibility to detect a response	Additional Cost of implementation	Implementation feasability	Impact on current data collected	crew safety	Industry support	Total Score 2	Grand Total
Modify mesh slack			1	1				2		2		-1			2	3	5
Magnetic, E+ metals, electrical deterent	1					-1		0		2	-1	-1			1	1	1
Turtle/shark lights for gillnet	1				2		-1	2		2	-1	2			2	5	7
Reduction of soaking time	2	2			2			6	-1	2		2			-1	2	8
Restriction of setting time	1	1		1	2			5	-1	2		2			-1	2	7
Fleet communication	2	2			2			6			2	2		2	2	8	14
Enforcement of safe handling and release				2	2			4		2		2	2	2	2	10	14
Workshop/training				2	2			4		2	-1	2	2	2	2	9	13

Table S2d. Mitigation options and ranking against criteria for rod and reel.

	Biological and Environmental impact								Fisheries impact and control								
Recreational fisheries/ Rod and reel	Reduce interaction	Minimize discards	Facilitate escape	Improve survivorship	Other bycatch*	Environmental impact	Carbone footprint	Total Score 1	Target species Impact	Technical feasibility to detect a response	Additional Cost of implementation	Implementation feasability	Impact on current data collected	crew safety	Industry support	Total Score 2	Grand Total
circle hook				2	1			3	2	2		2			2	8	11
Prohibition of live bait	2				2			4	1		2	2			2	7	11
Fleet communication	2				2			4			2	2		2	2	8	12
Enforcement of safe handling and release				2	2			4		2		2	2	2	2	10	14
Workshop/training				2	2			4		2	-1	2	2	2	2	9	13