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REVIEW

Bycatch mitigation of protected and threatened species in tuna purse seine and longline fisheries

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ABSTRACT: Bycatch and mortality in fishing gear poses a conservation threat worldwide to many marine species. Resource managers and conservation scientists face challenges in identifying bycatch mitigation solutions that work for multiple taxa while maintaining acceptable levels of target fish catch. The most successful mitigation measures to address bycatch concerns are those that (1) minimize bycatch with limited or no impact on target species catch, (2) have been proven through at-sea experimental research, (3) are practical, affordable, and easy to use, and (4) do not risk the safety of the fishing vessel crew or the bycaught animals. We conducted a review of mitigation measures in fishing gears that target tuna and tuna-like species and that either prevent capture of non-target species in fishing gear or facilitate alive post-capture release, and evaluated these against 4 defined criteria: effective, proven, practical, and safe. This paper outlines the most effective bycatch mitigation measures, as based upon the best scientific information available, in commercial and artisanal pelagic longline and purse seine fisheries, specifically those that target tuna and tuna-like species. This review includes information on gear and operational changes to fishing practices that reduce bycatch for protected and threatened species across taxonomic groups, with a focus on cetaceans, sea turtles, seabirds, sharks, and istiophorid billfishes. The information provided can guide future research and management efforts in Regional Fisheries Management Organizations that are specific to tuna fishing and that aim to minimize impacts to protected and threatened species while maintaining viable commercial fisheries.

KEY WORDS: Bycatch mitigation · Gear modification · Protected species · Marine fisheries · Tuna Regional Fisheries Management Organizations

1. INTRODUCTION

Bycatch and mortality in fishing gear poses a conservation threat worldwide to many protected and threatened marine species. This paper focuses on tuna fisheries due to their widespread distribution globally and to increasing pressures in international tuna Regional Fisheries Management Organizations (tRFMOs) to reduce the incidental capture of protected and threatened animals, including cetaceans, sea turtles, seabirds, sharks, and billfishes. Research on bycatch mitigation devices and techniques, or strategies that reduce mortality of incidentally caught animals, is ongoing throughout each ocean basin, with many fishers, managers and the general public hopeful to find solutions towards sustainable fisheries practices. For economic reasons, fishers often advocate for a conservation or engineering 'fix' in order to avoid fishery time or area fisheries closures (Campbell & Cornwell 2008). Because bycatch of multi-taxonomic groups occurs in some tuna fisheries, mitigation measures that are effective across taxa are needed (see Gilman et al. 2016b, 2019). The difficulties of identifying bycatch mitigation solutions that work for multiple taxa while maintaining target catch has hindered wider-scale adoption of several bycatch mitigation options, particularly within tRFMOs.

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There are several peer-reviewed papers assessing bycatch mitigation options for multiple taxa (Hall 1998, Werner et al. 2006, Beverly et al. 2009, Gilman et al. 2016b, 2019); however, the abundance of new research findings requires regular review of newer practices and their application to multiple species in different geographic areas. International workshops and scientific committee meetings of tRFMOs in recent years have focused on gear mitigation in specific fisheries (ISSF 2012, NMFS & ASMFC 2013, Wiedenfeld et al. 2015, Moreno et al. 2016) or for a single taxon (FAO 2018a). Where multiple species interact with a fishery, it is important to understand potentially conflicting mitigation outcomes (Hamilton & Baker 2019), and where mitigation measures can be effective across taxa.

In this paper, we review and synthesize information across gear types, tRFMO fisheries, and certain taxa in order to provide guidance on the most current and promising practices for mitigating bycatch ideally across species. This review is inclusive of bycatch mitigation measures for pelagic longline and purse seine fisheries, which are the primary gear types associated with targeting tuna and tuna-like species. The review includes information on gear and operational changes to fishing practices that reduce bycatch of protected and threatened species across taxonomic groups, with a focus on cetaceans, sea turtles, seabirds, sharks, and billfish. The inventory is not inclusive of all methods developed and tested; instead, we focused on bycatch mitigation practices that meet criteria for being effective, proven, practical, and safe. We also identify cross-taxon bycatch solutions and highlight the need for additional research. We do not include a review of spatial and temporal closures, which can be effective at reducing interactions in identified hotspots for certain species and fishing activities. The intended use of this document is to inform scientific and management bodies of tRFMOs.

2. METHODS

Bycatch mortality is reduced either by avoiding capture and/or by increasing post-release survival (Zollett & Swimmer 2019). In this paper, we conducted a review whereby we focused on bycatch mitigation measures that avoid capture and increase immediate release (or escape) of live animals from gear, since the latter is a component of increasing post-release survival. We used a combination of search terms such as 'bycatch mitigation,' 'gear modification,' 'protected species bycatch,' 'bycatch mitigation techniques,' 'bycatch survival,' 'fishing strategies to reduce bycatch,' and 'bycatch reduction strategies' in an attempt to conduct a comprehensive search for literature pertaining to studies on reducing bycatch of marine mammals, sea turtles, seabirds, sharks and billfish. We searched broadly for information on marine mammals, sea turtles, seabirds, sharks, and billfish, which are legally protected or are a species of concern because of documented bycatch in a fishery. Due to limited research on bycatch mitigation techniques for marine mammals in tuna fisheries, we limited the scope of the paper to cetaceans rather than to all marine mammals.

We conducted our review by way of immersing ourselves in primary literature and seeking out grey literature from a combination of peer-reviewed journals, internet sources, presence at scientific committee meetings, including internal documents from international fisheries commissions. While the attempt was made to be systematic in our approach, it should more likely be described as an unstructured search methodology. We compiled and synthesized the available literature on conservation and fishing strategies, which included changes to fishing gear and practices, by taxon and by gear type. The scope of this paper addresses bycatch mitigation of cetaceans, sea turtles, seabirds, sharks, and billfish in pelagic longline and purse seine gears that currently are the primary gear types that target tuna and tuna-like species. In general, this meta-analysis serves to illuminate relative changes of bycatch rates in response to mitigation measures as opposed to comparing specific reported bycatch rates. One of the many problems associated with fisheries bycatch, in general, is the lack of accurate data on catch rates and inconsistent methods of data collection (e.g. measures of weights vs. individuals). Hence, this paper largely avoids these published rates, given a high degree of uncertainty and concern for accuracy.

We consulted peer-reviewed and unpublished papers, such as workshop and technical reports, journal articles, and government reports; international organization reports; and websites dedicated to bycatch (e.g. bycatch.org and bmis-bycatch.org), for research related to bycatch reduction and mitigation using gear engineering and modifications. Where possible, we also engaged with scientists who are actively engaged in bycatch reduction experiments.

We considered mitigation measures that either (1) prevent capture of non-target species in a fishing gear, or (2) facilitate post-capture release, both of which are designed to reduce mortality of incidentally caught animals. We then reviewed these mitigation measures against 4 criteria: effective, proven, practical, and safe.

• **Effective:** A measure that consistently and significantly (per original experiment) reduces the bycatch of a non-target species or a group of species without significantly decreasing catch of target species or increasing bycatch of other taxa. If efficacy is shown in the majority of at-sea studies reviewed for a taxon, it is noted as demonstrated efficacy. If efficacy is demonstrated in some studies or for some species but not others, then that is noted as inconsistent efficacy. In cases where research on a mitigation measure is limited but promising in reducing bycatch, then it is considered to have potential efficacy.

• **Proven:** A measure that has been demonstrated through multiple fishery-dependent experiments to significantly reduce bycatch. In the tables, we denote the number of studies that we reviewed for this paper to assess this criterion (see Tables 1 & 2). If there were >10 studies with adequate sample sizes consistently proving the efficacy of a measure, we considered that as highly proven. Between 5 and 10 studies was considered to be medium, and <5 studies as low.

• **Practical:** A measure that is relatively easy to use, widely available, affordable, does not add substantial time to fishing operations (to the extent that it would not be supported by fishers), does not significantly decrease target catch, and can withstand environmental and operational conditions.

• **Safe:** A measure that does not pose a safety risk to crew or to animals.

For each gear type, we include a table that evaluates each bycatch mitigation technique on these criteria (see Tables 1 & 2). Not all taxa for each gear type have a mitigation option that meets the aforementioned criteria. In those cases, given the critical conservation needs of many of these bycaught species, managers' only option may be to use a mitigation measure that either has potential efficacy or has been shown to have inconsistent results in bycatch reduction between trials.

The Seabird Bycatch Working Group of the Agreement on the Conservation of Albatrosses and Petrels (ACAP) regularly reviews mitigation practices for seabirds and identified 'best practices' for seabird bycatch reduction (as defined in ACAP 2016c). We incorporate those recommendations here. The ACAP working group has developed a definition of a 'best practice,' which largely overlaps with the criteria used in this paper, with the exception of an additional criteria for compliance.

3. RESULTS

Below we present the bycatch mitigation measures by gear type and taxon that meet the criteria defined above. The tables in the following sections summarize the information for each gear type by taxon. A check mark signifies meeting one of the criteria.

3.1. Pelagic longline

Bycatch mitigation in pelagic longline gear requires consideration of trade-offs between measures that reduce capture and those that do not reduce capture but may increase post-release survival. For instance, shallow-set gear often has a higher rate of interactions with sea turtles but higher rates of at-vessel and post-release survival than deeper-set gear. Thus, certain mitigation strategies discussed below may not result in fewer interactions but may result in lower immediate (at-vessel) mortality or may increase an animal's post-release survival, depending on the type and extent of injury. As with other mitigation measures, results may vary by species or taxon (Table 1), making it important to understand cross-taxa impacts of mitigation options. Mitigation measures for taxa caught on longline gear take advantage of changes in hook or fishing practices to reduce bycatch (Table 1).

3.1.1. Cetaceans

Our review found that using weak circle hooks or encasing the hook has the potential to reduce cetacean bycatch in longline fisheries, despite a concern that there have been limited robust studies on these techniques. Previous reviews (Clarke et al. 2014, FAO 2018a) also provide keen insight into many of these options for cetaceans in all gear types.

Weak and circle hooks. Weak circle hooks are constructed of thinner wire diameter than standard circle hooks of the same size, and are thus designed to straighten at a lower strain (pull) level than standard hooks (Serafy et al. 2012). Weak hooks are believed to 'exploit the size and weight disparity' among species and promote the release of larger, non-target or bycatch species, such as cetaceans, that could (if hooked) straighten the hook and escape while still retaining most of the target species catch (Bayse & Kerstetter 2010, Gilman 2011, Clarke et al. 2014). Early trials of weak hooks were conducted in the Gulf of Mexico in a yellowfin tuna (*Thunnus albacares*)

Table 1. Mitigation measures for cetaceans, sea turtles, seabirds, sharks, and billfish in pelagic longline gear, evaluated against criteria: effective, proven, practical, and safe. Efficacy is often species- and fishery-specific. Cells with check marks: criteria have been satisfied. Blank cells: either unknown or does not satisfy a criterion. SST: sea surface temperature

Mitigation measure	Taxon	Effective		
		Consistently decreases bycatch (efficacy demonstrated, inconsistent, or potential)	Does not decrease target catch	Does not increase catch of other bycaught taxa
Altering hook location or accessibility of bait				
Weak and circle hooks[1]	Cetaceans	Potential efficacy	Variable depending on hook size and species	✓
Large circle hooks[2]	Sea turtles	Demonstrated efficacy: decreases deep hookings	Variable depending on hook size and species	Variable depending on hook size and/or species
Finfish bait (instead of squid)[3]	Sea turtles	Demonstrated efficacy	Variable depending on species	Variable depending on hook size and/or species
Circle hooks[4]	Sharks	Inconsistent efficacy: depends on species and area	Variable depending on hook size and species	✓
Circle hooks[5]	Billfish	Inconsistent efficacy	✓	✓
Line weighting[6]	Seabirds	Demonstrated efficacy	✓	✓
Encasing catch/hook[7]	Cetaceans	Potential efficacy	✓	✓
Hook shielding devices[8]	Seabirds	Potential efficacy	✓	✓
Monofilament instead of wire leaders[9]	Sharks	Potential efficacy	✓	Seabird interactions may increase
Modifying depth				
Deep setting[10]	Sea turtles	Demonstrated efficacy		✓
Deep setting[11]	Billfish	Potential efficacy		✓
Adjusting gear setting or retrieval conditions				
Reducing soak duration[12]	Sea turtles	Demonstrated efficacy		✓
Reducing soak duration[13]	Sharks	Potential efficacy		✓
Limiting retrieval during daylight[14]	Sea turtles	Demonstrated efficacy		✓
Fishing outside of preferred thermal habitat (SST)[15]	Sea turtles	Potential efficacy		
Night setting[16]	Seabirds	Demonstrated efficacy		✓
Bird-scaring lines[17]	Seabirds	Demonstrated efficacy	✓	✓
Side sets[18]	Seabirds	Potential efficacy	✓	✓
Haul exclusion devices (e.g. brickle curtain)[19]	Seabirds	Demonstrated efficacy	✓	✓

[1]Gilman 2011, Clarke et al. 2014, McLellan et al. 2015, Bigelow et al. 2012; [2]Watson et al. 2004, 2005, Sales et al. 2010, Santos et al. 2012, Huang et al. 2016, Gilman & Huang 2017, Cooke & Suski 2004, Curran & Beverly 2012, Epperly et al. 2012, Clarke et al. 2014, Parga et al. 2015, Witzell 1999, Gilman et al. 2006b, Piovano et al. 2009, Yokota et al. 2009, Pacheco et al. 2011, Serafy et al. 2012, Andraka et al. 2013, Swimmer et al. 2017, Clarke 2017, Bolten & Bjorndal 2002, 2004, Swimmer et al. 2010, Gilman 2011, Reinhardt et al. 2017, Read 2007, Stokes et al. 2011, Gilman & Hall 2015; [3]Watson et al. 2005, Kiyota et al. 2004 Rueda et al. 2006, Brazner & McMillan 2008, Yokota et al. 2009, Báez et al. 2010, Stokes et al. 2011, Domingo et al. 2012, Foster et al. 2012, Santos et al. 2012, Clarke 2017; [4]Yokota et al. 2006a, Kim et al. 2006, 2007, Walsh et al. 2008, Carruthers et al. 2009, Ward et al. 2009, Sales et al. 2010, Afonso et al. 2011, Curran & Bigelow 2011, Pacheco et al. 2011, Afonso et al. 2012, Curran & Beverly 2012, Godin et al. 2012 Aneesh et al. 2013, Hannan et al. 2013, Fernandez-Carvalho et al. 2015, Gilman & Hall 2015, Huang et al. 2016, Reinhardt et al. 2018; [5]Kerstetter et al. 2003, Kerstetter & Graves 2006, 2008, Serafy et al. 2009, Ward et al. 2009, Pacheco et al. 2011, Diaz 2008, Robertson et al. 2010, 2013, Curran & Bigelow 2011, Graves et al. 2012, Andraka et al. 2013;

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longline fishery to determine whether they could reduce unwanted mortality of the much larger bluefin tuna (*T. thynnus*), with promising results (Foster & Bergmann 2010). Additionally, trials of variable strength hooks were conducted off Cape Hatteras in the western North Atlantic Ocean that found no reduction in targeted tuna or swordfish catch rates on weaker hooks (Bayse & Kerstetter 2010). This work was followed by trials in a Hawaii-based tuna longline fishery whereby the catch per unit effort (CPUE) of target and non-target species were compared between relatively strong (4.5 mm wire diameter) vs. weak (4.0 mm wire diameter) circle hooks of the same size. There were no significant CPUE differ-

Table 1 (continued)

Proven Demonstrated level of study (high: >10 studies; medium: 5–10; low: <5)	Practical Widely available	 Affordable	 Easy to use; withstands environmental and operational conditions	Safe To crew and animals
Low	✓	✓	✓	✓
High	✓	✓	✓	✓
High	✓	✓	✓	✓
High	✓	✓	✓	✓
Medium	✓	✓	✓	✓
High	✓	✓	✓	May increase safety concerns to crew
Low	No			✓
High	No			✓
Medium	✓	✓	✓	
Medium	✓	✓	✓	✓
Low	✓	✓		✓
Low	✓	✓	✓	✓
Low	✓	✓	✓	✓
Low	✓	✓	✓	✓
High	✓	✓	✓	✓
High	✓	✓	✓	✓
High	✓	✓		Entanglement of bird scaring lines is possible
Low	✓	✓	✓	✓
Low	✓	✓	✓	✓

[6]ACAP 2016a,b, Gianuca et al. 2013, Ochi et al. 2013, Jiménez et al. 2013, Robertson et al. 2013; [7]McPherson & Nishida 2010; Rabearisoa et al. 2012; [8]ACAP 2016c, Baker et al. 2016, Barrington 2016a, Sullivan et al. 2016; [9]Ward et al. 2008, Gilman et al. 2016a, Reinhardt et al. 2018; [10]Polovina et al. 2003, Gilman et al. 2006a, Beverly et al. 2009, Huang et al. 2016, Clarke 2017; [11]Beverly et al. 2009; [12]Watson et al. 2003, Yokota et al. 2006a, FAO 2009, Clarke 2017; [13]Carruthers et al. 2011; [14]Watson et al. 2003, Yokota et al. 2006a, FAO 2009, Clarke 2017; [15]Watson et al. 2005, Brazner & McMillan 2008, Howell et al. 2008, Kobayashi et al. 2008, Foster et al. 2012, Abecassis et al. 2013, Huang 2015, Swimmer et al. 2017; [16]Ashford et al. 1995, Duckworth 1995, Cherel et al. 1996, Moreno et al. 1996, Ashford & Croxall 1998, Klaer & Polacheck 1998, Brothers et al. 1999a,b, McNamara et al. 1999, Weimerskirch et al. 2000, Belda & Sánchez 2001, Sánchez & Belda 2003, Reid et al. 2004, Gilman et al. 2005, Melvin et al. 2013, 2014, ACAP 2016d; [17]Melvin et al. 2001,Sullivan & Reid 2002, Melvin 2003, Melvin et al. 2004, Reid et al. 2004, ACAP 2016a,b; [18]Gilman et al. 2005; [19]Brothers et al. 1999a, Sullivan 2004, Otley et al. 2007, Reid et al. 2010, Gilman & Musyl 2017

ences for the 22 species analyzed, with the exception of more yellowfin tuna caught on weaker hooks (Bigelow et al. 2012). Current regulations in Hawaii's deep set (tuna) fishery require use of circle hooks with a maximum wire diameter size of 4.5 mm (and an offset of 10° or less) in order to reduce mortality and serious injury with false killer whales *Pseudorca crassidens*. Despite efforts to quantify the efficacy of weak hooks to reduce cetacean bycatch in longline gear, empirically derived estimates have been limited due to very low interaction rates in commercial fisheries coupled with the difficulty of observing such interactions. The rarity of the interactions also impedes research aimed to identify effective mitigation methods based on robust studies. However, research with animal cadavers demonstrated that polished steel and small hook gapes are likely to reduce serious injury if using weak hooks in a fishery (McLellan et al. 2015). Future experimental trials are planned to compare catch rates of target and bycatch species caught on hooks with different wire diameter measurements (4.5 vs. 4.2 mm) in Hawaii's tuna fishery in order to provide additional empirical data on the potential for weak hooks as an effective conservation tool.

Encasement of catch to reduce depradation. Physical barriers that drop over or encapsulate a fish caught on a hook may protect hooked fish from marine mammal depredation (Clarke et al. 2014). Reducing depredation interactions is believed to reduce adverse effects, such as hooking and entanglement of cetaceans. For pelagic fisheries, a barrier device would need to deploy immediately after hooking to protect the targeted catch and block the hook, as has been studied in a Patagonian toothfish (*Dissostichus eleginoides*) fishery (Rabearisoa et al. 2012). Some of the physical barriers that have been developed and/or tested include net-sleeves and sheaths, streamers made of plastic tubes, monofilament or wires, as well as metallic elements that disrupt marine mammal echolocation (McPherson & Nishida 2010). To date, we are unaware of similar trials in fisheries targeting tunas. For fishermen to adopt these devices and for them to be considered effective mitigation measures, the physical barriers need to be inexpensive, easy to use, and reduce marine mammal hooking.

3.1.2. Sea turtles

In the last 2 decades, research has focused on sea turtle bycatch reduction in pelagic longline fisheries. Most of the studies have focused on the effects of hook type, size, and offset, as well as bait type and hook depth as they relate to the likelihood of catching a sea turtle. Overall, using large circle hooks with a moderate (<10° offset) and finfish (preferably whole) bait and setting hooks deeper in the water column has demonstrated high efficacy (Watson et al. 2005, Serafy et al. 2012, Swimmer et al. 2017). Reducing soak duration during daylight hours has also been shown to effectively reduce sea turtle bycatch (Watson et al. 2003, 2005).

Hook and bait effects. Research and management measures to reduce sea turtle bycatch in longline gear have focused on hook attributes (shape and minimum width) and bait type, such as fish or squid (Watson et al. 2005, Swimmer et al. 2017). While many of these effects are related to a combination of the hook/bait attributes, single-factor effects have also been demonstrated and discussed (Swimmer et al. 2017). Large circle hooks (16/0 or greater) and whole finfish bait reduced sea turtle bycatch and the deep ingestion in the gut of hooks when compared to J and tuna hooks with squid bait. Large circle hooks have been previously defined as size 16/0 (minimum width: 4.4 cm) or larger (Clarke 2017).

Large circle hooks. In general, 4 hook types are used in pelagic longline fisheries: circle, J, tuna, and teracima. The first 3 are more common and have been relatively well studied with respect to their likelihood of catching sea turtles. Circle hooks are circular or oval shaped with the point turned back towards the shank, making the point less exposed than traditional J-shaped hooks (Cooke & Suski 2004). Circle hook designs generally range in size from '8/0' to '18/0', and are also defined by the degree to which the point (barb) deviates, or is offset, relative to the hook shank. A non-offset hook has the point in the same plane as the shaft, whereas an offset hook has the point bent sideways, usually within 25°, relative to the shank (Swimmer et al. 2010). Numerous studies have identified that the use of circle hooks reduces the incidental capture of sea turtles as well as the likelihood of deep-hookings and presumed mortality in longline gear (Watson et al. 2005, Gilman et al. 2006a, Sales et al. 2010, Santos et al. 2012, Huang et al. 2016, Gilman & Huang 2017, Swimmer et al. 2017). Deep-hookings result from a hook being swallowed and are presumed to have higher probability of post-release mortality as compared to a superficial (e.g. flipper) hooking or becoming entangled in the line (Ryder et al. 2006, Swimmer & Gilman 2012). Additionally, circle hooks with little or no offset tend to result in more hookings in the corner of the mouth (Cooke & Suski 2004, Curran & Beverly 2012, Epperly et al. 2012, Clarke et al. 2014, Parga et al. 2015) when compared with other hook types. Use of relatively large circle hooks (16/0 or greater) has been shown to reduce deep hooking of hard-shelled turtles (Witzell 1999, Watson et al. 2005, Gilman et al. 2006b, Clarke et al. 2014, Clarke 2017). Leatherback sea turtles are frequently externally hooked on the body or flippers, or become entangled in line (Watson et al. 2005). Gilman & Huang (2017) have a reported lower rate of leatherback bycatch on circle hooks than on J hooks of a similar size.

Relatively large circle hooks have been demonstrated to catch fewer sea turtles when compared to J hooks in numerous studies (Watson et al. 2005, Piovano et al. 2009, Yokota et al. 2009, Sales et al. 2010, Curran & Bigelow 2011, Pacheco et al. 2011, Santos et al. 2012, Serafy et al. 2012, Swimmer et al. 2017). Andraka et al. (2013) found hooking rates of green and olive ridley sea turtles were reduced by over 50% when using 16/0 circle hooks compared with the traditional tuna-hooks used in longline fisheries in the Eastern Tropical Pacific. In Costa Rica, an even greater reduction of sea turtle bycatch was observed with 18/0 circle hooks when compared with 16/0 circle hooks (Andraka et al. 2013). After mandatory use of large circle (16/0 or larger) hooks in 2 US-managed longline fisheries in the Pacific and Atlantic oceans, leatherback and loggerhead turtle bycatch rates declined significantly, and reductions were attributed to the use of both large circle hooks (18/0 and 16/0) and limited use of squid bait (Swimmer et al. 2017). This finding is consistent with ecological modeling of longline fisheries observer data from the Western Pacific Ocean that found that large circle hooks (16/0 or greater) and whole finfish bait contributed to significant decreases in turtle–longline interaction rates (Clarke 2017).

Comparisons of non-offset circle hooks and circle hooks with a 10° offset have shown similar catch rates and hooking locations (Bolten & Bjorndal 2002, 2004, Watson et al. 2004, Swimmer et al. 2010). However, at some greater offset, the gap becomes large enough to catch turtles at rates similar to the J hooks (Gilman 2011). Current US regulations aimed to minimize sea turtle bycatch regulate that circle hook offsets not exceed 10°.

Catch rates of target species on circle hooks compared to J hooks have varied by species and area (see Andraka et al. 2013, Huang et al. 2016, Reinhardt et al. 2018). Performance of circle hooks can vary based on hook shapes and sizes, bait type, species involved, fishing techniques, region, and other variables (Gilman et al. 2006b, Read 2007, Serafy et al. 2012, Andraka et al. 2013). Hook size may affect catch rates of species with relatively small mouths (Stokes et al. 2011, Gilman & Hall 2015).

Bait type. Based on results of numerous investigations, there is general consensus that replacing squid bait with fish bait will reduce sea turtle bycatch, and thus it is considered an effective bycatch mitigation practice (Watson et al. 2005, Yokota et al. 2009, Santos et al. 2012). Use of whole finfish bait versus squid bait has been shown to result in lower catch rates and, in many cases, lower incidence of deep-hooking (and presumed mortality) of longline-caught sea turtles (Kiyota et al. 2004, Watson et al. 2005, Brazner & McMillan 2008, Yokota et al. 2009, Santos et al. 2012). This effect of bait type on sea turtle bycatch may be related to the feeding behavior of sea turtles; loggerhead turtles in captivity have been observed to tear or bite pieces of fish on hooks, while they fully ingest the hook when squid are used as bait (Kiyota et al. 2004, Stokes et al. 2011).

Numerous of studies have demonstrated decreases in sea turtle bycatch when circle hooks and whole fish bait have been used simultaneously (Watson et al. 2004, Gilman et al. 2007, Pacheco et al. 2011, Santos et al. 2012, Swimmer et al. 2017). Swimmer et al. (2017) examined 20 yr of fisheries observer data and found that with the implementation of regulations (circle hooks and fish bait) in US longline fisheries, sea turtle bycatch declined in the Northeast Distant US fishing area in the Atlantic by 40% for leatherback and 61% for loggerhead turtles. For Hawaii's shallow-set fishery, leatherback bycatch declined by 84% and loggerhead bycatch declined by 95%, which was attributed in part to factors such as changes in hook and bait type (Swimmer et al. 2017).

Deep-setting. Sea turtles spend the majority of their time in the upper column (<~40 m) (Polovina et al. 2003), which explains why rates of interactions in shallow-set longline fisheries are an order of magnitude higher than on deep-set gear (Gilman et al. 2006a, Beverly et al. 2009). In a deep-set fishery targeting tuna in the tropical Atlantic Ocean, Huang et al. (2016) found that 64% of bycaught leatherback turtles were hooked on the first or second branchline closest to the float, suggesting turtles' greater vulnerability to capture at shallower depths. This vulnerability is likely due to the high degree of overlap between turtles' preferred depth in the epipelagic and the placement of hooks (Swimmer et al. 2017). Despite the significantly greater likelihood of capture in shallow-set gear, the probability of immediate survival is nearly 100% when baited hooks are within ~40 m of the surface and when actions are taken to handle turtles safely (Gilman et al. 2006a, Swimmer et al. 2006, see Zollett & Swimmer 2019). Delayed mortality of sea turtles captured and released from longline gear because of injury has been estimated to range between 19 and 82%, largely dependent on the type of injury, the amount of gear left on the turtle, and the general handling of the turtle (Swimmer et al. 2006, 2013).

Eliminating shallow hooks of a deep-set pelagic longline fishery has been proposed (Polovina et al. 2003) and tested (Beverly et al. 2009) as a bycatch mitigation strategy. Beverly et al. (2009) experimented with hooks deeper than 100 m in a Hawaii-based tuna fishery and found similar catch rates of bigeye tuna compared with control sets. However, they also found significantly lower catch rates of other high market-value species, such as wahoo *Acanthocybium solandri*, blue marlin *Makaira nigricans*, striped marlin *Kajikia audax*, and shortbill spearfish *Tetrapturus angustirostris*. Whether it is possible to offset some of the losses resulting from the elimination of shallow hooks would need to be evaluated on a fishery-specific basis. This strategy likely has a high conservation value and therefore is included in the list of effective mitigation practices, but the potential revenue loss needs to be evaluated as it could have significant economic impact in some fisheries, a topic that has been previously explored (Watson & Bigelow 2014, Gilman et al. 2019).

Gear deployment. Deploying gear before sunrise to reduce daylight hook soak duration may reduce sea turtle bycatch in longline fisheries (FAO 2009). In the western North Pacific, a study that compared bycatch rates on hooks retrieved after sunrise with those retrieved before sunrise indicated that shortening daylight soak time would reduce bycatch of loggerhead sea turtles (Yokota et al. 2006a). Similarly, in the western North Atlantic, loggerhead turtle bycatch rates increased significantly as daylight hook soak time increased (Watson et al. 2003, 2005). These studies suggest that modifying time of day and soak duration during daylight could be explored as options for reducing sea turtle bycatch in longline fisheries.

Sea surface temperature (SST) is a major driver that influences sea turtle distribution, suggesting that modifying fishing locations can reduce sea turtle bycatch. Studies have documented clear thermal habitat preferences for certain species in certain areas. In the western North Atlantic, fishing in SST below 20°C significantly reduced interactions with loggerhead sea turtles while increasing swordfish catch (Watson et al. 2005). In the Pacific, temperatures associated with the highest bycatch risk ranged from ~17 to 18.5°C for both loggerheads and leatherbacks (Howell et al. 2015, Swimmer et al. 2017). Both temperature ranges are consistent with previous research (Watson et al. 2005, Brazner & McMillan 2008, Howell et al. 2008, 2015, Kobayashi et al. 2008, Foster et al. 2012, Abecassis et al. 2013, Huang 2015). An internet-based product which analyzes SST and predicts areas likely to be preferred sea turtle habitat is available and may be useful to fishers and resource managers in making real-time decisions to reduce sea turtle bycatch in longline fisheries (Howell et al. 2008, 2015). This idea for real-time management has also gained considerable traction recently, particularly in Southern California where there has been extensive development in species' predictive habitat or distribution models for the purposes of dynamic fisheries management (Hazen et al. 2018). Models are developed for both target and bycatch species using telemetry data and observer data to predict co-occurrence probabilities that can be used to create time and area closures that meet demands of industry and conservation efforts. More work is currently underway to expand species' predicted locations into applied management.

3.1.3. Seabirds

Seabirds can become hooked or entangled in longline gear while foraging on bait or offal discard and subsequently drown as gear is deployed or retrieved. Many seabirds hooked during retrieval may be released alive with careful handing (ACAP 2016a). Post-release survival for seabirds remains largely unknown but is presumed to be low. ACAP recognizes a number of mitigation measures as 'best practice,' discussed below. Offal management, or the process of discarding fishing waste away from the side of the vessel during hauling, can effectively divert birds away from hooks. In addition, efforts that avoid spatial and temporal peaks of seabird foraging activity as well as use of water jet devices can deter seabirds from foraging close to the vessel and reduce rates of interactions. More recently, hook shielding devices have also been identified as an effective bycatch mitigation method. Additional strategies that are either under development or that have been not been shown to be effective bycatch reduction strategies are discussed in ACAP (2016 a,b,c), while recent measures considered by fishermen, but yet to be fully tested, to address increasing seabird bycatch in the Hawaii longline fisheries are discussed and prioritized by the Western Pacific Regional Fishery Management Council (WPRFMC 2019).

Line weighting. Seabird mortalities can be reduced by limiting the time birds can attack bait from deployment until submerging to an inaccessible depth during line-setting in a pelagic longline operation. Branch line weighting quickly sinks baited hooks out of range of feeding seabirds (Sullivan et al. 2012). Studies have demonstrated that a weighted mass positioned close to the hooks allows for sinking to occur rapidly and consistently (Robertson et al. 2010, 2013), reduces seabird attacks on baits (Gianuca et al. 2013, Ochi et al. 2013), and diminishes seabird mortalities (Jiménez et al. 2013). Weights on the hooks are also effective and have shown no negative effects on target catch rates (Gianuca et al. 2013, Jiménez et al. 2013, Robertson et al. 2013, ACAP 2016a,b). Line weighting improves the efficacy of other mitigation measures (e.g. night setting and bird-scaring lines) (Brothers 1991, Boggs 2001, Brothers et al. 2001, Sakai et al. 2001, Anderson & McArdle 2002, Hu et al. 2005, Melvin et al. 2013, 2014), but human safety concerns have been raised and must be considered (Melvin et al. 2013, 2014). ACAP (2016b) guidelines further specify recommended weights and distances from the hook configurations, such as (a) 40 g or greater attached within 0.5 m of the hook; (b) 60 g or greater attached within 1 m of the hook; or (c) 80 g or greater attached within 2 m of the hook. Compared with other seabird mitigation measures, fishery managers can implement and monitor consistent use of proper line weighting with relative ease (ACAP 2016a); however, one must also incorporate aspects of human safety, given the potential danger to fishermen who may be injured, should a line break under tension. To minimize potential danger, use of sliding leads that slide down the branch line during bite-offs, or when the line breaks under tension, are encouraged (Sullivan et al. 2012).

Bird-scaring lines (*tori lines*). Seabird mortalities associated with pelagic longline gear can be reduced through use of properly designed and deployed bird-scaring lines, also known as tori lines (Melvin et al. 2014, Domingo et al. 2017). Bird-scaring lines are attached at a high point at the stern of the vessel and to an object towed behind the vessel. Long and short, brightly colored streamers are attached to this line at specified intervals, which deters birds from flying to or under the line and diving for baited hooks. Because bird-scaring lines only provide protection to baited hooks within the area protected by their aerial extent, they should be used in combination with weighted branch lines and night setting, per ACAP recommendations, given that this combination allows lines to sink out of the reach of most diving birds (ACAP 2016a,b).

The efficacy of bird-scaring lines in reducing seabird bycatch in pelagic longlines is largely dependent upon the number of lines and design, aerial coverage, species present, the addition of multiple mitigation measures, as well as proper use. Several studies have demonstrated increased efficacy of 2 or more lines over a single line (Melvin et al. 2001, 2004, 2014, Sullivan & Reid 2002, Melvin 2003, Reid et al. 2004).

Recommendations for employing bird-scaring lines include using strong, fine lines and attaching them to the longline vessel with a barrel swivel. These specifications are intended to reduce the weight so that the part in the air — the aerial extent — extends farther astern, while a barrel swivel is used to keep the line from spinning on itself, preventing streamers from rolling up on the line (see ACAP 2016a). To increase tension, towed objects should be attached at the terminus of the bird-scaring line. Minimum standards are specified for vessels greater than and less than 35 m in length, due to vessel size-related differences in operation and gear type (see ACAP 2016a,b).

Night setting. Because seabirds are generally inactive at night, setting longlines at night is a highly effective strategy to reduce incidental mortality of seabirds, particularly when combined with weighted branch lines and bird-scaring lines (Ashford et al. 1995, Duckworth 1995, Cherel et al. 1996, Moreno et al. 1996, Ashford & Croxall 1998, Klaer & Polacheck 1998, Brothers et al. 1999a,b, McNamara et al. 1999, Weimerskirch et al. 2000, Belda & Sánchez 2001, Sánchez & Belda 2003, Reid et al. 2004, Gilman et al. 2005, Melvin et al. 2013, 2014). Night-setting, however, is not as effective for crepuscular/nocturnal foragers (e.g. white-chinned petrels *Procellaria aequinoctialis*), during bright moonlight, or if a vessel uses intense deck lights (see ACAP 2016a,b). Additionally, efficacy is also limited in high latitudes during the summer when the time between nautical dusk and dawn is minimal. In areas that overlap the range of white-chinned petrels, setting should be completed a minimum of 3 h before sunrise to avoid predawn feeding activity.

Hook-shielding devices. Hook-shielding devices are another method used in pelagic longline fishing to ensure baited hooks are set below the foraging depth of most seabirds. The devices are effective by shielding hooks to a prescribed depth (minimum of 10 m) or until after a minimum period of immersion (minimum of 10 min) (ACAP 2016c). Currently, 2 devices have been assessed and meet the ACAP requirements necessary to be considered a 'best practice.' The hookpod is a device that includes a weight (minimum 68 g) that is positioned at the hook, encapsulating the barb and point of the hook during setting. It remains attached until it reaches 10 m in depth and then releases the hook (Barrington 2016a, Sullivan et al. 2016, Debski et al. 2018). The hookpod would have cross-taxa benefits (e.g. turtles) if the device can be opened at even greater depth, and this option is currently being explored. The other option is the 'smart tuna hook,' which includes a weight (minimum 40 g) that is positioned at the hook, encapsulating the barb and point of the hook during setting and remaining attached for a minimum period of

10 min after setting, when the hook is then released (Baker et al. 2016, Barrington 2016b).

These devices are stand-alone measures; however, they both protect hooks and increase their sink rate, reducing opportunities for seabird interactions with longline gear. The ACAP (2016a) recognized hook-shielding devices as a best-practice seabird mitigation option, providing a stand-alone alternative to their established advice which recommends the simultaneous use of branchline weighting, night setting, and bird-scaring lines.

Bird deterrent curtains. A bird or 'brickle' curtain is a deterrent device that is composed of vertical hanging streamers supported by poles that create a protective barrier around the area of gear retrieval and can reduce seabird bycatch in longline fishing (Brothers et al. 1999a, Sullivan 2004, Otley et al. 2007, Reid et al. 2010). While it was originally intended for use in demersal longline fisheries, it can also be used in used in pelagic longlining where the branchline comes up at or aft of the stern, especially on larger high-seas longline vessels. Similar to other mitigation measures, there is a general consensus of a higher probability of reduced bycatch when exclusion devices are paired with other mitigation measures, including bird-scaring lines at setting, line weighting, night setting, and judicious offal management. Since some species (e.g. the black-browed albatross *Thalassarche melanophris* and cape petrel *Daption capense*) can become habituated to the curtain, it should be used strategically, such as during periods of high densities of birds around the hauling bay (Sullivan 2004).

Exact designs are not specified, but the curtain should function to deter birds from flying into the area where the line is being hauled and to prevent birds on the surface from swimming into the hauling bay area.

Side sets. In an experimental trial in pelagic longline gear, Gilman et al. (2005) found that setting gear from the side instead of the stern of the vessel, in combination with a bird curtain, resulted in the lowest bycatch of black-footed albatross *Phoebastria nigripes* and Laysan albatross *P. immutabilis* as compared to underwater setting chutes and blue-dyed bait. The efficacy of side-setting appears highly dependent upon its use with other mitigation methods, such as line weighting and bird curtains (Gilman et al. 2016a). While it has been effective in reducing seabird bycatch in Hawaii longline fisheries, more research should be undertaken to determine the versatility of this method on a range of vessel sizes, under various conditions, and also specific to the assemblage of seabirds vulnerable to a fishery.

3.1.4. Sharks

Bycatch of select shark populations is a conservation concern due to high shark catch rates, relatively low reproductive output, and low potential for population recovery (Gallagher et al. 2014). Some fisheries target sharks, while in other fisheries, they are caught incidentally. In fisheries where the catch is unwanted, mitigation measures can be considered for reducing shark bycatch. To date, deep-sets, reduced soak time, avoiding wire leader, and hook and bait changes are the most effective measures to reduce shark bycatch in longline fisheries.

Deep-sets. Catch rates vary among shark species, depending on the depth of baited hooks (Clarke et al. 2014). In an experimental fishery in Hawaii, removing branchlines shallower than 100 m had no significant impact on reducing shark catch rates (Beverly et al. 2009), while other studies suggest that setting gear deeper (e.g. >100 m) reduces shark catch rates (Fowler 2016). Some shark species (e.g. blue sharks *Prionace glauca* and silky sharks *Carcharhinus falciformis*) have been found to have higher catch rates on shallow-set gear, while results have been inconsistent for other species (e.g. mako sharks *Isurus oxyrinchus*) (Rey & Munoz-Chapuli 1991, Williams 1998, Simpfendorfer et al. 2002). Pelagic sharks have species-specific preferences in depth and temperature (Musyl et al. 2011); deep sets may reduce interactions with epipelagic shark species but increase fishing mortality for mesopelagic sharks. Habitat utilization data from numerous species suggest that setting gear at particular depths to avoid all sharks may be ineffective and overly simplistic (Clarke et al. 2014).

Reduced soak times. Some research has investigated whether limiting soak time can reduce shark catches (Watson et al. 2005, Carruthers et al. 2011). Given that soak time is essentially increased effort, the real question is how soak time influences shark survival, which varies dependent upon shark species. Some species have been found to have high on-hook survival (e.g. blue shark, other large shark species) (Ward et al. 2004, Diaz & Serafy 2005, Campana et al. 2009), which is likely a function of branchline length and the ability to swim and effectively respire while hooked (Heberer et al. 2010). Shark species' vulnerability to survival of fishing gear has been previously reviewed, with clear differences among species' blood chemistry, fight time, and survival (Gallagher et al. 2014, see Reinhardt et al. 2018).

Wire (steel) leader ban. Many countries have banned wire leaders in longline fisheries because they have higher shark catch rates than monofilament or nylon leaders. While caught alive on wire leaders (also known as 'steel trace') (WCPFC 2013), sharks can remain hooked for hours until gear retrieval occurs.

When using nylon or monofilament leaders, hooked sharks can bite the leader and swim away, thereby resulting in a lower catch rate of sharks hauled on board (Ward et al. 2008, Gilman et al. 2016b, Reinhardt et al. 2018). These 'bite-offs' are not generally recorded and thus there is limited information regarding accuracy of catch rates and post-interaction survival rates (Ward et al. 2008, Campana et al. 2009, Afonso et al. 2012). However, it is well established that use of wire leaders results in higher retention of sharks, and Australia banned the use of wire leaders in its eastern tuna longline fishery in 2005 with the specific intention to reduce unwanted shark bycatch.

Hook type and size. Overall, research results on the effects of hook and bait changes on shark catch rates have varied depending on hook types, size and offset, bait types, hooking location, region, and species (Afonso et al. 2012, Godin et al. 2012, Serafy et al. 2012, Reinhardt et al. 2018). This variability is not surprising, given the wide diversity in target and bycatch species and operational fishing factors that differ among studies. Hook and bait effects are confounding, but we address single-factor impacts when possible. Some studies have found that use of circle hooks can reduce catch rates of blue sharks in the Pacific, some by as much as 17–28% (Yokota et al. 2006b, Walsh et al. 2008, Ward et al. 2009, Curran & Bigelow 2011, Curran & Beverley 2012). However, lost revenue due to lower catch rates of incidental catch with high commercial value (e.g. juvenile tunas and billfishes) is a concern (Curran & Bigelow 2011). Circle hooks are also associated with lower capture risk for several other shark species in additional studies (Kim et al. 2006, 2007, Aneesh et al. 2013). However, 2 meta-analyses using published data (Gilman et al. 2016b, Reinhardt et al. 2018) indicate that certain species of sharks are captured more frequently on circle hooks as compared to J or tuna hooks. In the Atlantic Ocean, experimental longline fisheries found that catch rates of blue, silky, and oceanic whitetip (*C. longimanus*) sharks were significantly higher with 18/0 circle hooks than 9/0 J hooks (Afonso et al. 2011). Additional experimental fisheries in the Atlantic also found that blue shark catch rates were higher on circle hooks (Sales et al. 2010, Huang et al. 2016). Of concern, however, is a high variation in robustness of the studies, with some species' sample sizes fewer than 15 individuals per study (e.g. Afonso et al. 2011 that had fewer than 15 silky and oceanic whitetip sharks per study), thereby limiting the reliability of the meta-analysis findings. Another concern is over interpretation of equivocal findings, such as with the case of shortfin mako sharks, whereby one study found higher catch on circle hooks (Domingo et al. 2012), while another found higher catch on J hooks (Mejuto et al. (2008). This was the general conclusion of a third meta-analysis on this subject whereby 23 studies were analyzed with the conclusion that there were no significant differences in overall shark catch rates between circle hooks and J or tuna hooks (Godin et al. 2012). Of note are the numerous individual studies that demonstrate that hook type has no effect on catch rates for numerous shark species (Yokota et al. 2006b, Pacheco et al. 2011, Curran & Beverly 2012, Fernandez-Carvalho et al. 2015). These highly variable findings highlight the difficulty in drawing definitive conclusions regarding the role of hook type on catchability of certain species, thereby limiting ability to make conclusive statements regarding effective mitigation by taxa.

Despite the variability in catch rates by hook type, one finding is consistent: at-vessel and presumed post-release survival for sharks caught on circle hooks is higher compared to J or tuna hooks (see meta-analysis by Godin et al. 2012, Gilman et al. 2016b, Reinhardt et al. 2018). Results of meta-analyses suggest that sharks are more likely to survive if released when caught on circle hooks as compared to other hook types. Fernandez-Carvalho et al. (2015) found that on circle hooks, night (*C. signatus*), blue, silky, and oceanic whitetip sharks are more commonly hooked externally than internally, with a higher likelihood of long-term survival. Similarly, Carruthers et al. (2009) reported higher at-vessel survival for porbeagle *Lamna nasus* and blue sharks caught on circle hooks.

Size of circle hooks (measured by minimum width) also influences species and size selectivity both in target species and non-target shark species. Studies in the Gulf of Mexico found that circle hooks had higher catch rates than J hooks for Atlantic sharpnose (*Rhizoprionodon terraenovae*) and blacknose (*C. acronotus*) sharks, which was attributed to the narrower minimum width of the circle hooks (Hannan et al. 2013). The results of this study suggest that small sharks may be more susceptible to capture on circle hooks than J hooks and underline the importance of understanding species- and size-specific vulnerabilities, especially if mandating the use of a specific hook type or size (Hannan et al. 2013). However, no observed differences were noted between hook size and shark capture rates by several other studies (Yokota et al. 2006b, Pacheco et al. 2011, Afonso et al. 2012, Curran & Beverly 2012).

Bait. The role of bait type as a single factor has resulted in inconclusive findings. A meta-analysis of bycatch rates in 8 fisheries in addition to other studies suggested that squid bait would result in higher shark catch rates (Gilman et al. 2008, Godin et al. 2012). Capture rates of blue sharks in the Atlantic were lower using fish than squid bait (Watson et al. 2005, Foster et al. 2012), while one study found higher catch of blue sharks with mackerel bait as compared to squid (Coelho et al. 2012). Bait may also influence hooking location, though this may also vary by species (see Epperly et al. 2012). For blue and porbeagle sharks, gut hooking was higher with mackerel baits (Epperly et al. 2012), which may have effects on survivability. Gilman et al. (2008) documented early studies on the use of artificial baits with mixed results in Peru, Alaska, and Hawaii. Artificial baits have also been recommended for future studies as a potential mitigation method, but they would need to be designed to repel sharks or other bycatch while maintaining target species catch (Clarke et al. 2014). Despite numerous attempts initiated by industry and other scientists to test artificial baits, there is no clear winner in this category to date.

More work is needed to isolate the effects of single factors, such as bait type, hook shape, leader material, and hook size in order to identify a mitigation measure that accounts for the trade-offs between catch rates and rates of survival.

3.1.5. Istiophorid billfish

There has been limited bycatch reduction research on billfish to date, though billfish catch is a concern in some fisheries. Using circle hooks and eliminating shallow-sets are the most effective mitigation measures for reducing billfish mortality in longline gear. Setting deeper has some potential efficacy.

Circle hooks. Similar to results from shark research, a number of studies demonstrate that capture on circle hooks, when compared with J hooks, decreases the frequency of internal hooking, trauma, and post-release mortality for billfish (Kerstetter et al. 2003, Kerstetter & Graves 2006, 2008, Graves et al. 2012). Much research to date has focused on recreational fisheries. In commercial fisheries, billfish catch is complicated, since billfish are targeted in some fisheries and bycatch in others. In a meta-analysis on the use of circle hooks in recreational and commercial hook-and-line fisheries that interact with billfishes, Serafy et al. (2009) found that there were no significant differences in catch rates between the hook types. However, there were significant differences in mortality rates and rates of deep-hooking and bleeding; higher rates of survival were associated with circle hooks relative to J hooks.

In US recreational fisheries for billfishes, which are primarily catch-and-release, studies have shown that use of circle hooks results in higher rates of external hooking and post-release survival than use of traditional J hooks (Graves et al. 2012). Similarly, Pacheco et al. (2011) found that when comparing 18/0 non-offset circle hooks and 9/0 10° offset J hooks in the pelagic longline fishery for tuna and swordfish in equatorial waters off Brazil, circle hooks resulted in lower mortality of billfish and were more likely to hook target and bycatch species externally. Specifically, sailfish *Istiophorus platypterus* had higher catch rates on J hooks than circle hooks, and capture on circle hooks resulted in significantly higher rates of survival for blue and white (*K. albidus*) marlin (Diaz 2008). In Hawaii's longline fishery targeting tuna, Curran & Bigelow (2011) calculated that use of large 18/0 circle hooks had the potential to reduce mortality rates of billfish species by 29 to 48%.

A few studies have reported that circle hook use led to increased catch rates of billfish species. Andraka et al. (2013) found increased catch rates of sailfish associated with use of circle hooks (16/0) as compared to tuna hooks in Costa Rican waters. Circle hook catch rates for striped marlin exceeded catch rates on tuna hooks in eastern Australia (Ward et al. 2009). If billfish are more likely to be hooked externally, survival is still likely to be higher on circle hooks if fishers catch and release billfish following safe handling practices. Given the higher rates of post-release survivability, circle hook use for billfish is the most effective conservation measure currently.

Deep-setting. Understanding species' vertical distribution patterns can play an important role in the design of effective bycatch mitigation practices. Bycatch of pelagic billfish can be reduced by fishing at relatively greater depths. In experimental fishing gear, eliminating shallow-set hooks (<100 m) resulted in statistically fewer blue marlin, striped marlin, and shortbill spearfish in the Hawaii-based pelagic tuna fishery; targeted bigeye tuna catch rates were similar on control and experimental sets (Beverly et al. 2009). According to industry, the experimental gear required additional time setting and retrieving gear; however, this drawback can be overcome with increased use.

3.1.6. Cross-taxa considerations

Across taxa, a number of options have been confirmed or presumed to have conservation value to reduce bycatch in longline gear, including use of large circle hooks (with a minimal offset), use of fish bait (instead of squid), setting of gear deep (or removing shallow hooks from deep-sets), reduction of daytime soak duration, avoidance of wire leaders, use of 'weak' hooks, and shielding weighted hooks. Many of these mitigation measures can be used simultaneously to benefit several species across taxa that may be incidentally caught.

Most research to date has focused on gear changes (e.g. hook shape, hook size, hook offset, bait type, and leader material). For example, in most cases, circle hooks and whole finfish bait reduce sea turtle bycatch and deep-hooking when compared to J hooks with squid bait. These measures have also shown promise to reduce bycatch of cetaceans, billfish, and some shark species. Regulations requiring use of fish bait to reduce bycatch, specifically for sea turtles, need to consider the potential target species catch loss and the potential increase in catch of certain sharks or other vulnerable species (Foster et al. 2012, Gilman et al. 2016b). As with other bycatch mitigation methods, success in adopting these measures may be fishery dependent, though the majority of studies indicate a higher probability of immediate and post-release survival of sea turtles when both fish bait and circle hooks are used.

Sharks exhibited the greatest variability in response to mitigation measures. Such inconsistency in results, in addition to expense and human safety concerns, has been seen in studies of electropositive and magnetic repellents as mitigation measures (Gilman et al. 2008, Stoner & Kaimmer 2008, Brill et al. 2009, O'Connell et al. 2011, 2014, Robbins et al. 2011, Hutchinson et al. 2012, Patterson et al. 2014, Favaro & Côté 2015), deeming these measures no longer warranting additional studies. Banning wire leaders to reduce shark bycatch, however, is highly promising given that it is effective, easy to implement, easy to enforce, requires minimal expenditure, and does not reduce catch rates of targeted species (Ward et al. 2008). In addition, wire leaders can be used to facilitate branchline weighting to avoid seabird interactions (Sullivan et al. 2012); therefore, a wire leader ban could inadvertently increase seabird–gear interactions unless alternative seabird mitigation measures are adopted.

Altering hook location/accessibility, setting gear deep, and changing soak time and duration have all shown promising results for multiple taxa. Night sets, which result in reduced seabird bycatch, often attract fish through the use of colored lightsticks, which have been implicated in the attraction of sea turtles to baited hooks. This has been supported by captive studies which indicate that limits to gear illumination at night may reduce sea turtle bycatch (Lohmann & Wang 2006, Lohmann et al. 2006); however, the expected loss of target species without lights during night sets prevents fishermen from testing the idea. As such, it is therefore deemed impractical to ever be adopted in a fishery (Swimmer et al. 2017). Exploring use of other light frequencies that either attract or have no impact on fish species while simultaneously deterring sea turtles could be valuable for further research. Exploiting differences between the visual systems of targeted species and bycatch species may, in a general sense, prove useful for bycatch mitigation and has been proposed previously (Southwood et al. 2008, Jordan et al. 2013).

In an effort to reduce billfish bycatch, understanding and exploiting differences in sensory or physiological capabilities, or bait preferences between species, have been proposed (Swimmer & Wang 2007), yet to date, research is limited or non-existent. Perhaps more valuable in the near term is to improve understanding of vertical distributions in the water column so as to minimize overlap between billfish and other targeted species that may inhabit different depths, as this would be a mitigation method that would be relatively easy to achieve.

3.2. Purse seine

Purse seine fishing is generally conducted by deploying nets around fish aggregating devices (FADs), free-swimming tuna schools, or aggregations of tunas and dolphins. Until recently, cetacean-associated sets were only known to occur in the Eastern Pacific Ocean (EPO) due to unique cetacean behaviors; however, new research quantifies these interactions in the tropical Atlantic and Indian Oceans and reports high cetacean survival rates (Escalle et al. 2015). Due to the associative behavior of the principal tropical tuna species (skipjack, bigeye, and yellowfin) with floating objects, purse-seine fishers regularly deploy drifting FADs (dFADs) to more efficiently increase their catches (Scott & Lopez 2014). As such, the rate of dFAD use has dramatically increased globally over recent decades (Davies et al. 2014, Scott & Lopez 2014, Griffiths et al. 2019). dFADs comprise a surface raft and a submerged appendage, most often made of plastics, including nylon nets, buoys and polypropylene ropes (FAO 2018b). The submerged appendages are mostly made of old netting material, reaching on average 50 m depth but can reach up to 80 m depth for some fleets, and are known to entangle non-targeted species (Davies et al. 2014). Due to the complexity of FAD fishing strategy, in which FADs are left drifting with a geo-locating buoy, it is estimated that a substantial proportion dFADs that are deployed by purse seines are lost or abandoned every year (Moreno et al. 2016, FAO 2018b). Negative ecological impacts caused by active as well as lost and abandoned dFADs are numerous (see Gaertner et al. 2015, FAO 2018b). Of particular concern is ghost fishing, whereby lost/abandoned or derelict FADs and material contribute directly to mortality of non-targeted species (FAO 2018b, Gaertner et al. 2015). More recent non- and less-entangling FADs are in commercial use in some regions (ISSF 2016), as has been required by 3 of the 4 tRFMOs. Research is underway to modify dFADs with non-entangling and biodegradable materials in order to minimize the ecosystem-level impacts, and these findings will ideally be incorporated into RFMO conservation measures in the near future.

Currently, all tRFMOs have management measures in place aimed to either limit the number of FADs deployed (e.g. via time and area closures of purse seines or annual limits) and/or use of biodegradable and non-entangling materials etc. (Restrepo et al. 2019). The International Seafood Sustainability Foundation (ISSF) has initiated numerous collaborations with industry that have resulted in guides and best practices that have been widely accepted both by industry and as management guidance within RFMOs (ISSF 2019, Restrepo et al. 2019). One of the many obstacles for improved FAD management relates to a lack of established common definitions across RFMOs for FADs, such as what defines a 'FAD,' 'buoy,' 'active' vs. 'inactive,' etc. Because of this, FAD data submitted to tRFMOs are limited, thereby creating confusion and limits to efficacy with regards to FAD management on a global level. Harmonization of terms across tRFMOs is likely to be a critical early step for improved FAD management on a global level (IATTC 2019).

The present review focuses on drifting, as opposed to anchored FAD designs. The mitigation measures with demonstrated efficacy to avoid interactions or reduce mortality of bycaught cetaceans, sea turtles, seabirds, sharks, and billfish focus on avoiding capture or entanglement and facilitating escape are summarized in Table 2.

3.2.1. Cetaceans

Cetacean interactions with purse seine gear most commonly occur with dolphins in the EPO, and the

Table 2. Mitigation measures for marine mammals, sea turtles, and sharks in purse seine gear, evaluated against the promising practice criterion (e.g. effective, proven, practical, and safe). Cells with check marks: criteria have been satisfied. Blank cells: either unknown or does not satisfy a criterion. FAD: fish aggregating device

Mitigation measure	Taxon	Effective: Consistently decreases bycatch (efficacy demonstrated, inconsistent, or potential)	Effective: Does not decrease target catch	Effective: Does not increase catch of other bycaught taxa
Changing fishing practices				
Backdown procedure[1]	Cetaceans	Demonstrated efficacy	✓	✓
Avoiding dolphins sets[2]	Cetaceans	Demonstrated efficacy	✓	✓
Aid in release[3]	Cetaceans	Demonstrated efficacy	✓	✓
Restricting FAD use[4]	Sea turtles	Potential efficacy		✓
Restricting FAD use[5]	Sharks	Potential efficacy		✓
Preventing entanglement				
Medina panel[6]	Cetaceans	Demonstrated efficacy	✓	✓
Modifying FADs[7]	Sea turtles	Potential efficacy	✓	✓
Modifying FADs[8]	Sharks	Potential efficacy	✓	✓

[1]Northridge & Hofman 1999, AIDCP 2009, Hall & Roman 2013; [2]Hall et al. 2000; [3]AIDCP 2009, Gosliner 1999; [4]Bourjea et al. 2014, Stelfox et al. 2014; [5]Filmalter et al. 2013, ISSF 2016; [6]Barham et al. 1977, Northridge & Hofman 1999; [7]Restrepo et al. 2017, 2019, Moreno

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strategies below have been developed for the fishery in this area. While the best practice is to avoid setting on dolphins, the strategies below are useful in situations when a dolphin (or dolphins) becomes incidentally captured despite dolphin sets being avoided. Quick and careful release of the animals will lead to a higher likelihood of post-capture survival. Hamilton & Baker (2019) have recently published on the minimal mitigation methods available across fisheries, highlighting an urgent need for future development in this field. Work by Escalle and colleagues (Escalle et al. 2015) indicates an abundance of interactions between purse seine gear and cetaceans, with limited observed trips recording 122 baleen whales and 72 delphinids captured. The observations also indicate high apparent immediate survival rates (Atlantic Ocean: 92 %, Indian Ocean: 100 %).

The Agreement on the International Dolphin Conservation Program (AIDCP) requires a number of measures that reduce dolphin mortality in the tuna purse seine fishery in the EPO. These measures include a backdown procedure to release all live dolphins, Medina panels to prevent entanglement, release of dolphins with assistance from dedicated crew, a ban on night sets, required training courses for fishermen, and catch limits per vessel (dolphin mortality limits) (AIDCP 2009). These measures have demonstrated efficacy and have been required in the EPO for years.

Backdown procedure. Fishermen created a practice known as the backdown procedure, which allows encircled dolphins to swim over and out of the net. The procedure requires vessels to reverse after encircling the catch, attaching the pursed net to the vessel side and reversing engines so that the encirclement is elongated out ahead of the vessel and the far end of the net is pulled below the surface, providing an escape for captured dolphins (Northridge & Hofman 1999). The AIDCP requires the backdown to continue until the release of all live dolphins from the net (AIDCP 2009).

Medina panel. The Medina panel, named after the fisherman who invented it, was invented to aid in escape of dolphins from nets. It consists of replacing large mesh in the upper portions of the purse seine with small-mesh netting, reducing the likelihood of entanglement when dolphins swim over the net during the backdown procedure (Barham et al. 1977, Northridge & Hofman 1999). The ability to perform backdown procedure may be limited to vessels fishing in the EPO.

Changing fishing practices. Other successful mitigation measures include modifications to fishing practices by avoiding large groups of dolphins, decreasing sets around dolphins, and reducing sets with strong currents (Hall et al. 2000). While fishing at night may be an effective method, it has not been experimentally tested, and there are concerns that fishing at night would prevent fishermen facilitating a safe escape if an animal is captured. AIDCP requires that the backdown procedure be complete at least 30 min before sunset

Table 2 (continued)

Proven Demonstrated level of study (high: >10 studies; medium: 5–10; low: <5)	Practical Widely available	 Affordable	 Easy to use; withstands environmental and operational conditions	Safe To crew and animals
Low	✓	✓	Slightly increases hauling time	✓
Low	✓	✓	May be limited only to sets that target yellowfin and dolphin species associated with yellowfin	✓
Low	✓	✓	Increases hauling time	Increases interactions with cetaceans but also post-release survival
Low	✓	✓	✓	✓
Low	✓	✓	✓	✓
Low	✓	✓	✓	✓
Medium	✓	✓	✓	✓
Medium	✓	✓	✓	✓

et al. 2016, Franco et al. 2012; [8]Chanrachkij et al. 2008, Franco et al. 2012, Fowler 2016, Moreno et al. 2016, Restrepo et al. 2017, Lopez et al. 2019

(AIDCP 2009). The AIDCP also requires that crew aid in dolphin escape (AIDCP 2009); one way this is accomplished is through use of a small rescue raft and other means of hand rescue of dolphin from the net during fishing operations (Hall 1998, Gosliner 1999).

3.2.2. Sea turtles

Due to the relatively low interaction rate and because sea turtles are generally captured and released alive (Kelleher 2005, Amandè et al. 2010), there has been less research on sea turtle bycatch mitigation in purse seine gear than in longline or gillnet gear. However, mitigation strategies with potential efficacy for reducing sea turtle bycatch in purse seine gear involve limiting dFADs sets and modifying FAD designs to reduce entanglements. Specifically, non-entangling netting or other material should be used in the construction of FADs in a manner that prevents turtle entanglement or underwater entrapment (Murua et al. 2017, Restrepo et al. 2017).

Changing fishing practices. Successful strategies to reduce sea turtle interactions in purse seine gear include (from FAO 2009, 2018a, ISSF 2010, Gilman 2011, Murua et al. 2017, Restrepo et al. 2017):

- Restricting setting on FADs or other aggregating devices, including logs, floating debris, whales, whale sharks, and data buoys
- Monitoring FADs and safely releasing FAD-entangled sea turtles
- Recovering FADs when not in use to prevent ghost fishing
- Avoiding encircling sea turtles during fishing operations
- Minimizing use of entangling materials in FADs
- Deploying boats to spot and release entangled turtles, including those that may be entangled during net rolling

In light of the numerous ecological concerns associated with FAD use, efforts are underway to provide guidance towards best practices and management for fleets particularly in tropical tuna purse seine fisheries (Restrepo et al. 2019).

Modifying FADs, biodegradable FADs. Research is currently underway to determine if modifying FAD designs (e.g. non-entangling and biodegradable) can reduce sea turtle entanglements (Murua et al. 2017, Restrepo et al. 2017). Gear changes include modifying netting materials for FAD underwater appendages, such as using rigid netting materials (Chanrachkij et al. 2008), using a cylindrical curtain of fabric instead of conventional netting for the FAD appendage (Molina et al. 2005), or removing netting (Franco et al. 2012). Further, making FADs biodegradable can reduce ghost fishing (Chanrachkij et al. 2008, Lopez et al. 2019, Moreno et al. 2018). New FAD designs without hanging nets have been developed and tested to reduce ghost fishing and bycatch (Franco et al. 2009, 2012, Moreno et al. 2018), and FADs without netting have been considered to have minimal risk of entanglement (ISSF 2019). Given a relatively high loss rate of FADs in all ocean basins, and their potential to wash up on beaches and remain caught on reef systems (FAO 2018b, Escalle et al. 2019), all attempts to limit FAD use will have positive effects on coastal ecosystems. FADs made of various biodegradable materials are also being developed and tested to determine the most appropriate materials to aggregate fish and to last the appropriate amount of time (e.g. 5 mo to 1 yr, depending on the ocean) (Franco et al. 2012, Lopez et al. 2019, Moreno et al. 2016).

Although most of these practices are still in the development phase, interviews with skippers and fisheries managers have identified features for effective FADs. These features aim to effectively aggregate tuna, minimize mortality of non-target species, avoid detection of FADs by competing vessels, use readily available and low-cost materials, and allow easy on-board construction (Franco et al. 2009, 2012). To minimize bycatch and maintain target catch, as well as to minimize ecological impacts, the following specifics should be followed:

- Avoid hanging net panels with mesh large enough to cause entanglement
- Avoid covering with layers of net which can cause entrapment
- Reduce the surface area of the raft to prevent turtles from ‘hauling out’ on the raft
- Be made from biodegradable materials (as far as possible)
- Be opaque to light or dark to generate shadow
- Have underwater structures to allow fouling organisms to settle
- Be safe for the crew
- Allow attachment of satellite buoys

(modified from Franco et al. 2009, 2012, Hampton et al. 2017, ISSF 2019, Restrepo et al. 2019).

3.2.3. Seabirds

Seabird bycatch in purse seine gear is limited and generally considered ‘not problematic’ (Gilman 2011). However, in certain non-tuna-targeting fisheries where bycatch is high, such as is the case for flesh-footed shearwaters *Puffinus carneipes* in the Western Australia pilchard purse seine fishery (in Baker & Hamilton 2016), ACAP (2016c) determined that the most effective mitigation must include night fishing and spatial closures that can be identified based on spatial and temporal conditions associated with bycatch. Given the limited research in this area, especially in tuna fisheries, we did not have sufficient studies to analyze in Table 2.

3.2.4. Sharks

Sharks, particularly juveniles associated with floating objects, are known to be caught in FADs associated with purse seine fishing (Filmalter et al. 2013, Hall & Roman 2013, Davies et al. 2014, Poisson et al. 2014, Fowler 2016, Restrepo et al. 2017). With the increased use of artificial FADs over the past decade, there has been a significant increase in shark bycatch and mortality. Most sharks caught on FADs are silky sharks (Gilman 2011, Filmalter et al. 2013, Hall & Roman 2013, Davies et al. 2014, Poisson et al. 2014). Currently, the mitigation measures with potential efficacy for sharks include limiting FAD use and modifying FAD designs and practices (Davies et al. 2014, Peatman & Pilling 2016, Restrepo et al. 2017). Additional mitigation measures considered but that do not meet the standards of the criteria include shark repellents (associated with FADs), bait stations to lure sharks from FADs, and timing sets when silky sharks are least likely to be associated with FADs (e.g. at night) (see Gilman 2011).

Modification to FAD design and sets. Shark mortality occurs through entanglement in nets hung under drifting FADs (Filmalter et al. 2013, Fowler 2016). Several practices under consideration by RFMOs echo those presented for sea turtles and include (adapted from Fowler 2016, Restrepo et al. 2017):

- Setting on free-swimming tuna schools instead of FADs
- Using chum to lure sharks away from FADs before the set is made
- Removing entangling FADs and replacing with improved designs (including biodegradable materials)
- Setting on FADs only when >10 tons of tuna are present
- Reporting FADs interactions to relevant RFMOs
- Ensuring all FADs are clearly identified
- Restricting the total number of deployed FADs
- Using spatial closures
- Developing national and fishery-wide FAD Management Plans

FADs should be designed with little or no risk of entanglement by avoiding entangling materials, such as netting (Hampton et al. 2017, Restrepo et al. 2017, 2019).

Shark bycatch is reported to be considerably higher in FAD sets than sets on free-swimming tuna (Filmalter et al. 2013, ISSF 2016). According to various ecological models, limiting sets to free-swimming tuna schools could reduce silky shark capture in the western and central Pacific by 83% (Peatman & Pilling 2016). More work is needed at the level of tRFMOs to address issues of shark bycatch specific to FADs and to engage in efforts to both limit and modify FAD design in order to reduce incidental shark mortality.

3.2.5. Istiophorid billfish

Billfish bycatch in purse seine fishing gear is relatively low (Gaertner et al. 2002, Hall & Roman 2013, Restrepo et al. 2017), resulting in limited research and identification of effective bycatch mitigation strategies. To date, studies have focused on understanding factors associated with habitat preferences (via SST, chlorophyll *a*) and subsequent higher vulnerability to capture (Prince & Goodyear 2006, Boyce et al. 2008, Mourato et al. 2010, Hoolihan et al. 2011, Martinez-Rincon et al. 2015). As such, these studies can be used to identify potential time area closures to minimize interactions with species of concern. Other research focuses on the tendency of billfish to aggregate around floating objects, which increases their vulnerability of being caught by purse seine gear. Findings suggest that most billfish catch rates are higher on FAD sets compared to unassociated sets (Hampton & Bailey 1993, Restrepo et al. 2017). Gaertner et al. (2002) found that a temporary moratorium on fishing with FADs in the eastern Atlantic Ocean resulted in a decrease in catches of marlins but increased sailfish catches. More research on reducing FAD associated sets is warranted.

3.2.6. Cross-taxa considerations

The need to manage at the level of ecosystem as opposed to single species or taxa is a given, yet can present numerous challenges for fisheries managers. For example, with respect to purse seine fisheries, the shift in effort to set on FADs as compared to setting on dolphins in purse seine fisheries has significantly reduced dolphin bycatch in the EPO (Jordan et al. 2013), but it has led to an increase in bycatch associated with FADs and unassociated sets, such as sea turtles, sharks, mobulid rays, and non-target teleost fish, as well as juvenile tunas (Hall 1998, Lewison et al. 2004, Hampton et al. 2017). Sets on unassociated schools are also likely to become even less economically viable as FAD use continues to expand despite the ecological disruptions attributed to their presence (Fonteneau et al. 2000, Marsac et al. 2000, Hallier & Gaertner 2008, Gilman 2011, Hall & Roman 2013). Several mitigation measures, particularly those that reduce the ability of FADs to entangle marine species, show promise in effectively reducing bycatch of other taxa in purse seine gear.

Restricting FAD use or FAD sets when certain taxa are present or modifying FADs to reduce entanglement are effective, cross-taxa solutions to addressing sea turtle, shark, and possibly billfish bycatch. While reducing entanglement in FADs will reduce bycatch of some species or taxa, others will still be at risk of capture due to their association with floating objects. It is important to consider how a change from FAD-associated sets to sets on unassociated schools would affect other species and to predict how this information can be used in management decisions, including the unpredictability of fishing on schools and fishing in the open seas in general. Similar concerns are raised in longline fisheries management with respect to managing for single taxa, such as sea turtles, versus the ecosystem at large (Gilman et al. 2019).

4. CONCLUSION

This review confirms an earlier conclusion that there is no 'one size fits all' solution for bycatch reduction across taxa (Hall et al. 2012, Gilman et al. 2016b, 2019). This is largely due to species having different physiological and behavioral responses to factors within taxa, across taxa, and even in different geographic settings. Managers must consider that bycatch mitigation meant to reduce interactions or mortality of one species or taxon may inadvertently affect catch and mortality of other taxa (Kaplan et al. 2007, Gilman & Huang 2017, Gilman et al. 2019). This review highlights certain gear modifications that could provide conservation benefits to >1 taxonomic group and discusses where trade-offs need to be considered between target catch rates and bycatch reduction.

Table 3. Effective mitigation measures for each taxon by gear type. FAD: fish aggregating device

Mechanism	Cetaceans	Sea turtles	Seabirds	Sharks	Billfish
Longline					
Gear changes (hook, bait, leader)	Weak and circle hooks	Large circle hooks Whole finfish bait		Circle hooks Bait changes Ban on wire leaders	Circle hooks
Making hooks inaccessible	Encasing catch/hook		Hook-shielding and bird exclusion devices Line weighting Bird scaring lines		
Depth		Deep sets		Deep sets	Deep sets
Soak time or duration		Reduced gear soak time	Night sets	Reduced gear soak time	
Purse seine					
Changes in fishing practices	Backdown procedure Medina panel Avoiding dolphin sets Avoiding night sets Using a raft to aid in release				
FAD-related modifications		Restricting no. of FAD sets Modifying FADs Avoiding FAD sets		Restricting no. of FAD sets Modifying FADs Avoiding FAD sets Luring sharks from FADs before sets	

Table 3 summarizes the most effective mitigation measures for each taxon by gear type, a few of which could be effective across multiple taxa. It also highlights areas where additional research is still needed due to gaps in effective mitigation measures.

Mitigation measures aimed to reduce bycatch of cetaceans, sea turtles, seabirds, sharks, and billfish in pelagic longline and purse seine gears are numerous and varied, and come with various trade-offs that must be considered and that have been previously discussed (Hall 1998, Gilman et al. 2019). We have presented many of these relevant trade-offs, such as target catch retention, bycatch species of concern, interaction rates, and post-interaction survival rates. Given that there will never be a one-size-fits-all for conservation, effective conservation will require a holistic approach that involves industry, scientists, and managers. Solutions are possible, and processes such as those inherent to regional fisheries management bodies can be avenues for change. However, it is incumbent upon scientists and policy-makers to work effectively in order to strike a balance between exploitation of marine resources while simultaneously maintaining marine ecosystem health.

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