



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 mod-

ification,' '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 incident-

tally 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	✓	✓

¹Gilman 2011, Clarke et al. 2014, McLellan et al. 2015, Bigelow et al. 2012; ²Watson 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, Andracka 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; ³Watson 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; ⁴Yokota 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; ⁵Kerstetter 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, Andracka 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 Hattaras 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			Safe To crew and animals
	Widely available	Affordable	Easy to use; withstands environmental and operational conditions	
Low	✓	✓	✓	✓
High	✓	✓	✓	✓
High	✓	✓	✓	✓
High	✓	✓	✓	✓
Medium	✓	✓	✓	✓
High	✓	✓	✓	May increase safety concerns to crew
Low	No			✓
High	No			✓
Medium	✓	✓	✓	
Medium	✓	✓	✓	✓
Low	✓	✓	✓	✓
Low	✓	✓	✓	✓
Low	✓	✓	✓	✓
High	✓	✓	✓	✓
High	✓	✓	✓	✓
High	✓	✓	✓	Entanglement of bird scaring lines is possible
Low	✓	✓	✓	✓
Low	✓	✓	✓	✓

⁶ACAP 2016a,b, Gianuca et al. 2013, Ochi et al. 2013, Jiménez et al. 2013, Robertson et al. 2013; ⁷McPherson & Nishida 2010; Rabearisoa et al. 2012; ⁸ACAP 2016c, Baker et al. 2016, Barrington 2016a, Sullivan et al. 2016; ⁹Ward et al. 2008, Gilman et al. 2016a, Reinhardt et al. 2018; ¹⁰Polovina et al. 2003, Gilman et al. 2006a, Beverly et al. 2009, Huang et al. 2016, Clarke 2017; ¹¹Beverly et al. 2009; ¹²Watson et al. 2003, Yokota et al. 2006a, FAO 2009, Clarke 2017; ¹³Carruthers et al. 2011; ¹⁴Watson et al. 2003, Yokota et al. 2006a, FAO 2009, Clarke 2017; ¹⁵Watson 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; ¹⁶Ashford et al. 1995, Duckworth 1995, Chérel 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; ¹⁷Melvin et al. 2001, Sullivan & Reid 2002, Melvin 2003, Melvin et al. 2004, Reid et al. 2004, ACAP 2016a,b; ¹⁸Gilman et al. 2005; ¹⁹Brothers 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 mitiga-

tion 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 depredation. 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, Pio-

vano 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, particu-

larly 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 handling (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 speci-

fications 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 falci-formis*) 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 branch-line 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 polypropy-

lene 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 of FADs 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 FADs 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 FADs 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)	Does not decrease target catch	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	✓	✓

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

(continued on next page)

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			Safe To crew and animals
	Widely available	Affordable	Easy to use; withstands environmental and operational conditions	
Low	✓	✓	Slightly increases hauling time May be limited only to sets that target yellowfin and dolphin species associated with yellowfin Increases hauling time	✓
Low	✓	✓		✓
Low	✓	✓		Increases interactions with cetaceans but also post-release survival
Low	✓	✓	✓	✓
Low	✓	✓	✓	✓
Medium	✓	✓	✓	✓
Medium	✓	✓	✓	✓

et al. 2016, Franco et al. 2012; ⁸Chanrachkij 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 (Mo-

lina 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 (Filmlalter 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, Filmlalter 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 (Filmlalter 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 (Filmlalter 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 man-

agement 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.

Acknowledgements. We thank the researchers and fishery industry participants who have conducted research to help us generate this paper. Critical reviews by and input from Bob Trumble, Kristy Long, Brian Stacy, Nina Young, Mi Ae Kim, Rachel O'Malley, Cheri McCarty, and Keith Bigelow have greatly improved this manuscript. NOAA Fisheries Office of International Affairs and Seafood Inspection provided funding for this project.

LITERATURE CITED

- Abecassis M, Senina I, Lehodey P, Gaspar P and others (2013) A model of loggerhead sea turtle (*Caretta caretta*) habitat and movement in the oceanic North Pacific. *PLOS ONE* 8:e73274
- ACAP (Agreement on the Conservation of Albatrosses and Petrels) (2016a) Review and best practice advice for reducing the impact of pelagic longline fisheries on seabirds. Seabird Bycatch Working Group, Ninth Meeting of the Advisory Committee, La Serena, 9–13 May 2016
- ACAP (2016b) ACAP review of seabird bycatch mitigation measures for pelagic longline fisheries. Seabird Bycatch Working Group, Ninth Meeting of the Advisory Committee, La Serena, 9–13 May 2016
- ACAP (2016c) ACAP review of seabird bycatch mitigation measures for demersal longline fisheries. Seabird Bycatch Working Group, Ninth Meeting of the Advisory Committee, La Serena, 9–13 May 2016
- ACAP (2016d) ACAP review and best practice advice for reducing the impact of pelagic longline fisheries on seabirds. Reviewed at the Ninth Meeting of the Advisory Committee, La Serena, 9–13 May 2016
- Afonso AS, Hazin FHV, Carvalho F, Pacheco JC and others (2011) Fishing gear modifications to reduce elasmobranch mortality in pelagic and bottom longline fisheries off Northeast Brazil. *Fish Res* 108:336–343
- Afonso AS, Santiago R, Hazina H, Hazina FHV (2012) Shark bycatch and mortality and hook bite-offs in pelagic longlines: interactions between hook types and leader materials. *Fish Res* 131–133:9–14
- AIDCP (Agreement on the International Dolphin Conservation Program) (2009) AIDCP amendment 2009, preamble. www.westcoast.fisheries.noaa.gov/publications/fishery_management/iattc_info/aidcp-amended-oct-2009.pdf
- Amandè MJ, Ariz J, Chassot E, Delgado de Molina A and others (2010) Bycatch of the European purse seine tuna fishery in the Atlantic Ocean for the 2003–2007 period. *Aquat Living Resour* 23:353–362
- Anderson S, McArdle B (2002) Sink rate of baited hooks during deployment of a pelagic longline from a New Zealand fishing vessel. *N Z J Mar Freshw Res* 36:185–195
- Andraka S, Mug M, Hall M, Pons M and others (2013) Circle hooks: developing better fishing practices in the artisanal longline fisheries of the Eastern Pacific Ocean. *Biol Conserv* 160:214–223
- Aneesh KV, Khanolkar PS, Pravin, P, Madhu VR, Meenakumari B (2013) Effect of hook design on longline catches in Lakshadweep Sea, India. *Indian J Fish* 60: 21–27
- Ashford JR, Croxall JP (1998) An assessment of CCAMLR measures employed to mitigate seabird mortality in longline operations for *Dissostichus eleginoides* around South Georgia. *CCAMLR Sci* 5:217–230
- Ashford JR, Croxall JP, Rubilar PS, Moreno CA (1995) Seabird interactions with longlining operations for *Dissostichus eleginoides* around South Georgia, April to May 1994. *CCAMLR Sci* 2:111–121
- Báez JC, Macías D, Puerto MA, Camiñas JA and others (2010) Análisis biométrico de la tortuga boba, *Caretta caretta* (Linnaeus 1758), en el Mediterráneo occidental. *Collective Volume Scientific Papers ICCAT (International Commission for the Conservation of Atlantic Tunas)* 65:2305–2309
- Baker B, Hamilton S (2016) Impacts of purse-seine fishing on seabirds and approaches to mitigate bycatch. Seventh Meeting of the Seabird Bycatch Working Group, La Serena, 2–4 May 2016. Agreement on the Conservation of Albatrosses and Petrels (ACAP)
- Baker GB, Candy SG, Rollinson D (2016) Efficacy of the 'Smart Tuna Hook' in reducing bycatch of seabirds in the South African pelagic longline fishery. In: ACAP – Seventh Meeting of the Seabird Bycatch Working Group. ACAP-SBWG7-Inf07. ACAP, Serena, Chile. www.acap.aq/working-groups/seabird-bycatch-working-group/seabird-bycatch-wg-meeting-7/sbwg7-information-papers/2719-sbwg7-inf-07-efficacy-of-the-smart-tuna-hook-in-reducing-bycatch-of-seabirds-in-the-south-african-pelagic-longline-fishery/file
- Barham E, Taguchi W, Reilly S (1977) Porpoise rescue methods in the yellowfin purse seine fishery and the importance of Medina Panel mesh size. *Marine Fish Rev* 39(5):1–10
- Barrington JHS (2016a) 'Hook Pod' as best practice seabird bycatch mitigation in pelagic longline fisheries. In: ACAP – Seventh Meeting of the Seabird Bycatch Working Group. ACAP-SBWG7-Doc10. ACAP, Serena, Chile. www.acap.aq/working-groups/seabird-bycatch-working-group/seabird-bycatch-wg-meeting-7/sbwg7-meeting-documents/2691-sbwg7-doc-10-hook-pod-as-best-practice

- seabird-bycatch-mitigation-in-pelagic-longline-fisheries/file
- Barrington JHS (2016b) 'Smart Tuna Hook' as best practice seabird bycatch mitigation in pelagic longline fisheries. In: ACAP – Seventh Meeting of the Seabird Bycatch Working Group. ACAP, Serena, Chile. ACAP-SBWG7-Doc9. www.acap.aq/working-groups/seabird-bycatch-working-group/seabird-bycatch-wg-meeting-7/sbwg7-meeting-documents/2689-sbwg7-doc-09-smart-tuna-hook-as-best-practice-seabird-bycatch-mitigation-in-pelagic-longline-fisheries/file
- Bayse SM, Kerstetter DW (2010) Assessing bycatch reduction potential of variable strength hooks for pilot whales in a western North Atlantic pelagic longline fishery. *J North Carolina Acad Sci* 126:6–14
- ✦ Belda EJ, Sánchez A (2001) Seabird mortality on longline fisheries in the western Mediterranean: factors affecting bycatch and proposed mitigating measures. *Biol Conserv* 98:357–363
- ✦ Beverly S, Curran D, Musyl M, Molony B (2009) Effects of eliminating shallow hooks from tuna longline sets on target and non-target species in the Hawaii-based pelagic tuna fishery. *Fish Res* 96:281–288
- ✦ Bigelow KA, Kerstetter DW, Dancho MG, Marchetti JA (2012) Catch rates with variable strength circle hooks in the Hawaii-based tuna longline fishery. *Bull Mar Sci* 88:425–447
- Boggs CH (2001) Detering albatrosses from contacting baits during swordfish longline sets. In: Melvin E, Parrish JK (eds) *Seabird bycatch: trends, roadblocks and solutions*. University of Alaska Sea Grant, Fairbanks, AK, p 79–94
- Bolten A, Bjørndal K (2002) Experiment to evaluate gear modification on rates of sea turtle bycatch in the swordfish longline fishery in the Azores. Final project report submitted to the US National Marine Fisheries Service. Archie Carr Center for Sea Turtle Research, University of Florida, Gainesville, FL
- Bolten A, Bjørndal K (2004) Experiment to evaluate gear modification on rates of sea turtle bycatch in the swordfish longline fishery in the Azores—phase 3. Final project report submitted to the US National Marine Fisheries Service. Archie Carr Center for Sea Turtle Research, University of Florida, Gainesville, FL
- Bourjea J, Clermont S, Delgado A, Murua H, Ruiz J, Ciccione S, Chavance P (2014) Marine turtle interaction with purse-seine fishery in the Atlantic and Indian oceans: lessons for management. *Biol Conserv* 178:74–87
- ✦ Boyce DG, Tittensor DP, Worm B (2008) Effects of temperature on global patterns of tuna and billfish richness. *Mar Ecol Prog Ser* 355:267–276
- ✦ Brazner JC, McMillan J (2008) Loggerhead turtle (*Caretta caretta*) bycatch in Canadian pelagic longline fisheries: relative importance in the western North Atlantic and opportunities for mitigation. *Fish Res* 91:310–324
- Brill R, Bushnell P, Smith L, Speaks C, Sundaram R, Stroud E, Wang J (2009) The repulsive and feeding-deterrent effects of electropositive metals on juvenile sandbar sharks (*Carcharhinus plumbeus*). *Fish Bull* 107:298–307
- ✦ Brothers NP (1991) Approaches to reducing albatross mortality and associated bait loss in the Japanese long-line fishery. *Biol Conserv* 55:255–268
- Brothers NP, Cooper J, Løkkeborg S (1999a) The incidental catch of seabirds by longline fisheries: worldwide review and technical guidelines for mitigation. *FAO Fish Circ No.* 937
- ✦ Brothers N, Gales R, Reid T (1999b) The influence of environmental variables and mitigation measures on seabird catch rates in the Japanese tuna longline fishery within the Australian Fishing Zone 1991–1995. *Biol Conserv* 88:85–101
- Brothers N, Gales R, Reid T (2001) The effect of line weighting on the sink rate of pelagic tuna longline hooks, and its potential for minimising seabird mortalities. *CCSBTERS/0111/53*. Report to the Fourth Meeting of the Ecologically Related Species Working Group, Commission for the Conservation of Southern Bluefin Tuna (CCSBT)
- ✦ Campana SE, Joyce W, Manning MJ (2009) Bycatch and discard mortality in commercially caught blue sharks *Prionace glauca* assessed using archival satellite pop-up tags. *Mar Ecol Prog Ser* 387:241–253
- ✦ Campbell LM, Cornwell ML (2008) Human dimensions of bycatch reduction technology: current assumptions and directions for future research. *Endang Species Res* 5:325–334
- ✦ Carruthers E, Schneider D, Neilson J (2009) Estimating the odds of survival and identifying mitigation opportunities for common bycatch in pelagic longline fisheries. *Biol Conserv* 142:2620–2630
- ✦ Carruthers EH, Neilson JD, Smith SC (2011) Overlooked bycatch mitigation opportunities in pelagic longline fisheries: soak time and temperature effects on swordfish (*Xiphias gladius*) and blue shark (*Prionace glauca*) catch. *Fish Res* 108:112–120
- Chanrachkij I, Siriraksophon S, Loog-on A (2008) Modifying the drifting fish aggregating devices to mitigate sea turtle mortality: a SEAFDEC initiative. Southeast Asian Fisheries Development Center, Bangkok
- ✦ Cheral Y, Weimerskirch H, Duhamel G (1996) Interactions between longline vessels and seabirds in Kerguelen waters and a method to reduce seabird mortality. *Biol Conserv* 75:63–70
- Clarke S (2017) Reducing ecosystem impacts of tuna fishing. Joint analysis of sea turtle mitigation effectiveness, final report 16–19 February 2016 & 3–8 November 2016. Common Oceans FAO GEF, Honolulu, HI
- Clarke S, Sato M, Small C, Sullivan B, Inoue Y, Ochi D (2014) Bycatch in longline fisheries for tuna and tuna-like species: a global review of status and mitigation measures. *FAO Fish Aquacult Tech Pap No.* 588. FAO, Rome
- Coelho R, Fernandez-Carvalho J, Lino PG, Santos MN (2012) An overview of the hooking mortality of elasmobranchs caught in a swordfish pelagic longline fishery in the Atlantic Ocean. *Aquat Living Resour* 25:311–319
- ✦ Cooke S, Suski C (2004) Are circular hooks an effective tool for conserving marine and freshwater recreational catch and-release fisheries? *Aquat Conserv* 14:299–326
- ✦ Curran D, Beverly S (2012) Effects of 16/0 circle hooks on pelagic fish catches in three South Pacific albacore longline fisheries. *Bull Mar Sci* 88:485–497
- ✦ Curran D, Bigelow K (2011) Effects of circle hooks on pelagic catches in the Hawaii-based tuna longline. *Fish Res* 109:265–275
- ✦ Davies T, Mees C, Milner-Gulland EJ (2014) The past, present and future use of drifting fish aggregating devices (FADs) in the Indian Ocean. *Mar Policy* 45:163–170
- Debski I, Clements K, Hjørvarsdóttir F (2018) Hook shielding devices to mitigate seabird bycatch: review of effectiveness. *WCPFC-SC14-2018/EB-WP-10*. In: Western and

- Central Pacific Fisheries Commission (WCPFC) Scientific Committee 14th Regular Session, Busan. <https://www.wcpfc.int/node/31014> (accessed 4 Dec 2020)
- ✦ Diaz G (2008) The effect of circle hooks and straight (J) hooks on the catch rates and numbers of white marlin and blue marlin released alive by the US pelagic longline fleet in the Gulf of Mexico. *N Am J Fish Manage* 28: 500–506 (accessed 4 Dec 2020)
- Diaz GA, Serafy JE (2005) Longline-caught blue shark (*Prionace glauca*): factors affecting the numbers available for live release. *Fish Bull* 103:720–724
- Domingo A, Pons M, Jimenez S, Miller P, Barcelo C, Swimmer Y (2012) Circle hook performance in the Uruguayan pelagic longline fishery. *Bull Mar Sci* 88:499–511
- ✦ Domingo A, Jiménez S, Abreu M, Forselledo R, Yates O (2017) Effectiveness of tori line use to reduce seabird bycatch in pelagic longline fishing. *PLOS ONE* 12:e0184465
- Duckworth K (1995) Analysis of factors which influence seabird bycatch in the Japanese southern bluefin tuna longline fishery in New Zealand waters, 1989–1993. *NZ Fish Assess Res Doc* 95/26
- ✦ Epperly SP, Watson JW, Foster DG, Shah AK (2012) Anatomical hooking location and condition of animals captured with pelagic longlines: the Grand Banks experiments 2002–2003. *Bull Mar Sci* 88:513–527
- ✦ Escalle L, Capietto A, Chavance P, Dubroca L and others (2015) Cetaceans and tuna purse seine fisheries in the Atlantic and Indian Oceans: interactions but few mortalities. *Mar Ecol Prog Ser* 522:255–268
- Escalle L, Muller B, Phillips JS, Brouwer S, Pilling G (2019) Report on analyses of the 2016/2019 PNA FAD tracking program. WCPFC-SC15-2019/MI-WP-12. In: 15th Regular Session of the Scientific Committee, Western and Central Pacific Fisheries Commission (WCPFC), Honolulu, HI. <https://www.wcpfc.int/meetings/15th-regular-session-wcpfc>
- FAO (2009) Guidelines to reduce sea turtle mortality in fishing operations. FAO, Rome
- FAO (2018a) Report of the Expert Workshop on Means and Methods for Reducing Marine Mammal Mortality in Fishing and Aquaculture Operations, Rome, 20–23 March 2018. FAO Fish Aquacult Rep No. 1231. FAO, Rome. www.fao.org/3/I9993EN/i9993en.pdf
- FAO (2018b) Stakeholders' views on methods to identify the ownership and track the position of drifting fish aggregating devices used by tuna purse seine fisheries with reference to the FAO Draft Guidelines on the Marking of Fishing Gear. In: Gilman E, Bigler B, Muller B, Moreno G and others (eds) FAO Fish Aquacult Tech Pap No. T631. FAO, Rome
- ✦ Favaro B, Côté IM (2015) Do by-catch reduction devices in longline fisheries reduce capture of sharks and rays? A global meta-analysis. *Fish Fish* 16:300–309
- ✦ Fernandez-Carvalho J, Coelho R, Santosa M, Amorim S (2015) Effects of hook and bait in a tropical northeast Atlantic pelagic longline fishery: Part II—target, bycatch and discard fishes. *Fish Res* 164:312–321
- ✦ Filmalter JD, Capello M, Deneubourg JL, Cowley PD, Dagorn L (2013) Looking behind the curtain: quantifying massive shark mortality in fish aggregating devices. *Front Ecol Environ* 11:291–296
- Fonteneau A, Pallares P, Pianet A (2000) A worldwide review of purse seine fisheries on FADs. In: Le Gall JY, Cayre P, Taquet M (eds) Pêche thonière et dispositifs de concentration de poissons. *Actes Colloq IFREMER* 28:15–35
- Fonteneau A, Chassot E, Gaertner D (2015) Managing tropical tuna purse seine fisheries through limiting the number of drifting fish aggregating devices in the Atlantic: food for thought. Conference Paper January 2015. Document SCRS/2014/133 Rev. International Commission for the Conservation of Atlantic Tunas (ICCAT)
- Foster D, Bergmann C (2010) Update on Gulf of Mexico pelagic longline bluefin tuna mitigation research. NOAA Fisheries, SWFSC interim report. Engineering and Harvesting Branch, NOAA
- ✦ Foster DG, Epperly SP, Shah AK, Watson JW (2012) Evaluation of hook and bait type on the catch rates in the western North Atlantic Ocean pelagic longline fishery. *Bull Mar Sci* 88:529–545
- Fowler SL (2016) Draft best practice mitigation guidelines for sharks and rays taken in purse seine and long-line fisheries. Memorandum of understanding on the conservation of migratory sharks. 1st Workshop of the CMS Sharks MOU Conservation Working Group, Bristol, 31 Oct–1 Nov 2016. CMS/Sharks/CWG1/Doc.3.2. <https://www.cms.int/sharks/en/CWG1>
- Franco J, Dagorn L, Sancristobal I, Moreno G (2009) Design of ecological FADs. IOTC-2009-WPEB-16. Working Party on Ecosystems and Bycatch, Indian Ocean Tuna Commission (IOTC)
- Franco J, Moreno G, López J, Sancristobal I (2012) Testing new designs of drifting fish aggregating device (DFAD) in Eastern Atlantic to reduce turtle and shark mortality. *Collect Vol Sci Pap ICCAT* 68:1754–1762
- Gaertner D, Mendard F, Develter C, Ariz J (2002) Bycatch of billfishes by the European tuna purse-seine fishery in the Atlantic Ocean. *Fish Bull* 100:683–689
- Gaertner D, Ariz J, Bez N, Clermidy S, Moreno G, Murua H, Soto M (2015) Catch, effort, and ecosystem impacts of FAD-fishing (CECOFAD). *Collect Vol Sci Pap ICCAT* 71: 525–539
- ✦ Gallagher A, Orbesen ES, Hammerschlag N, Serafy JE (2014) Vulnerability of oceanic sharks as pelagic longline bycatch. *Glob Ecol Conserv* 1:50–59
- Gianuca D, Peppes FV, César JH, Sant'Ana R, Neves T (2013) Do leaded swivels close to hooks affect the catch rate of target species in pelagic longline? A preliminary study of southern Brazilian fleet. SBWG5 Doc 33. Fifth Meeting of the Seabird Bycatch Working Group, La Rochelle, 1–3 May 2013. Agreement on the Conservation of Albatrosses and Petrels (ACAP)
- ✦ Gilman E (2011) Bycatch governance and best practice mitigation technology in global tuna fisheries. *Mar Policy* 35:590–609
- Gilman E, Hall M (2015) Potentially significant variables explaining bycatch and survival rates and alternative data collection protocols to harmonize tuna RFMOs' pelagic longline observer programmes. Appendix 1 to WCPFC-SC11-2015/EB-IP-05. Western and Central Pacific Fisheries Commission (WCPFC), Kolonia
- ✦ Gilman E, Huang H (2017) Review of effects of pelagic longline hook and bait type on sea turtle catch rate, anatomical hooking position and at-vessel mortality rate. *Rev Fish Biol Fish* 27:43–52
- Gilman E, Musyl M (2017) Captain and observer perspectives on the commercial viability and efficacy of alternative methods to reduce seabird bycatch during gear haulback in the Hawaii-based pelagic longline swordfish fishery. Grant report to the National Fish and Wildlife Foundation. Information Paper at the 8th Meeting of the

- Seabird Bycatch Working Group, Agreement on the Conservation of Albatrosses and Petrels (ACAP). <https://www.acap.org/documents/working-groups/seabird-bycatch-working-group/seabird-bycatch-wg-meeting-8/sbwg8-information-papers/2928-sbwg8-inf-23-perspectives-on-the-commercial-viability-and-efficacy-of-alternative-methods-to-reduce-seabird-bycatch-during-gear-haulback/file>
- ✦ Gilman E, Brothers N, Kobayashi D (2005) Principles and approaches to abate seabird bycatch in longline fisheries. *Fish Fish* 6:35–49
- ✦ Gilman E, Zollett E, Beverly S, Nakano H and others (2006a) Reducing sea turtle bycatch in pelagic longline gear. *Fish Fish* 7:2–23
- Gilman E, Kobayashi D, Swenarton T, Dalzell P, Kinan I, Brothers N (2006b) Efficacy and commercial viability of regulations designed to reduce sea turtle interactions in the Hawaii-based longline swordfish fishery. Western Pacific Regional Fishery Management Council (WPRFMC), Honolulu, HI
- ✦ Gilman E, Kobayashi D, Swenarton T, Brothers N, Dalzell P, Kinan-Kelly I (2007) Reducing sea turtle interactions in the Hawaii-based longline swordfish fishery. *Biol Conserv* 139:19–28
- ✦ Gilman E, Clarke S, Brothers N, Alfaro-Shigueto J and others (2008) Shark interactions in pelagic longline fisheries. *Mar Policy* 32:1–18
- ✦ Gilman E, Chaloupka M, Peschon J, Ellgen S (2016a) Risk factors for seabird bycatch in a pelagic longline tuna fishery. *PLOS ONE* 11:e0155477
- ✦ Gilman E, Chaloupka M, Swimmer Y, Piovano S (2016b) A cross-taxa assessment of pelagic longline bycatch mitigation measures: conflicts and mutual benefits to elasmobranchs. *Fish Fish* 17:748–784
- ✦ Gilman E, Chaloupka M, Dagorn L, Hall M and others (2019) Robbing Peter to pay Paul: replacing unintended cross-taxa conflicts with intentional tradeoffs by moving from piecemeal to integrated fisheries bycatch management. *Rev Fish Biol Fish* 29:93–123
- ✦ Godin AC, Carlson JK, Burgener V (2012) The effect of circle hooks on shark catchability and at-vessel mortality rates in longline fisheries. *Bull Mar Sci* 88:469–483
- Gosliner ML (1999) The tuna-dolphin controversy. In: Twiss JR, Reeves RR (eds) Conservation and management of marine mammals. Smithsonian Institution Press, Washington, DC, p 120–155
- ✦ Graves JE, Horodysky AZ, Kerstetter DW (2012) Incorporating circle hooks into Atlantic pelagic fisheries: case studies from the commercial tuna/swordfish longline and recreational billfish fisheries. *Bull Mar Sci* 88:411–422
- ✦ Griffiths SP, Allain V, Hoyle SD, Lawson TA, Nicol SJ (2019) Just a FAD? Ecosystem impacts of tuna purse-seine fishing associated with fish aggregating devices in the western Pacific Warm Pool Province. *Fish Oceanogr* 28:94–112
- ✦ Hall M (1998) An ecological view of the tuna–dolphin problem: impacts and trade-offs. *Rev Fish Biol Fish* 8:1–34
- Hall M, Roman M (2013) Bycatch and non-tuna catch in the tropical tuna purse seine fisheries of the world. *FAO Fish Aquacult Tech Pap No. 568*. FAO, Rome
- ✦ Hall MA, Alverson DL, Metzals KI (2000) By-catch: problems and solutions. *Mar Pollut Bull* 41:204–219
- Hall M, Swimmer Y, Parga M (2012) No ‘silver bullets’ but plenty of options: working with artisanal fishers in the Eastern Pacific to reduce incidental sea turtle mortality in longline fisheries. In: Seminoff JA, Wallace BP (eds) Sea turtles of the Eastern Pacific Ocean: advances in research and conservation. University of Arizona Press, Tucson, AZ, p 136–153
- ✦ Hallier JP, Gaertner D (2008) Drifting fish aggregation devices could act as an ecological trap for tropical tuna species. *Mar Ecol Prog Ser* 353:255–264
- ✦ Hamilton S, Baker BG (2019) Technical mitigation to reduce marine mammal bycatch and entanglement in commercial fishing gear: lessons learnt and future directions. *Rev Fish Biol Fish* 29:223–247
- Hampton J, Bailey K (1993) Fishing for tunas associated with floating objects: a review of the western Pacific fishery. Tuna and Billfish Assessment Programme Tech Rep no. 31. South Pacific Commission, Noumea
- Hampton J, Leape G, Nickson A, Restrepo V and others (2017) The impacts of FAD use on non-target species. Doc. No. j-FAD_21/2017. Joint t-RFMO FAD Working Group meeting. www.iccat.int/Documents/Meetings/Docs/2017_JFADS_REP_ENG.pdf
- ✦ Hannan KM, Fogg AQ, Driggers WB III, Hoffmayer ER, Ingram GW Jr, Grace MA (2013) Size selectivity and catch rates of two small coastal shark species caught on circle and J hooks in the northern Gulf of Mexico. *Fish Res* 147:145–149
- Hazen EL, Scales KL, Maxwell SM, Briscoe DK and others (2018) A dynamic ocean management tool to reduce bycatch and support sustainable fisheries. *Sci. Adv.* 4: eaar3001. doi:10.1126/sciadv.aar3001
- ✦ Heberer C, Aalbers SA, Bernal D, Kohin S, DiFiore B, Sepulveda CA (2010) Insights into catch-and-release survivorship and stress-induced blood biochemistry of common thresher sharks (*Alopias vulpinus*) captured in the southern California recreational fishery. *Fish Res* 106:495–500
- ✦ Hoolihan JP, Luo J, Goodyear CP, Orbesen ES, Prince ED (2011) Vertical habitat use of sailfish (*Istiophorus platypterus*) in the Atlantic and eastern Pacific, derived from pop-up satellite archival tag data. *Fish Oceanogr* 20:192–205
- ✦ Howell EA, Kobayashi DR, Parker DM, Balazs GH, Polovina JJ (2008) TurtleWatch: a tool to aid in the bycatch reduction of loggerhead turtles *Caretta caretta* in the Hawaii-based pelagic longline fishery. *Endang Species Res* 5:267–278
- ✦ Howell EA, Hoover A, Benson SR, Bailey H and others (2015) Enhancing the TurtleWatch product for leatherback sea turtles, a dynamic habitat model for ecosystem-based management. *Fish Oceanogr* 24:57–68
- ✦ Hu F, Shiga M, Yokota K, Shiode D, Tokai T, Sakai H, Arimoto T (2005) Effects of specifications of branch line on sinking characteristics of hooks in Japanese tuna longline. *Bull Jpn Soc Sci Fish* 71:33–38
- ✦ Huang HW (2015) Conservation hotspots for the turtles on the high seas of the Atlantic Ocean. *PLOS ONE* 10: e0133614
- ✦ Huang H, Swimmer Y, Bigelow K, Gutierrez A, Foster DG (2016) Influence of hook type on catch of commercial and bycatch species in an Atlantic tuna fishery. *Mar Policy* 65:68–75
- ✦ Hutchinson M, Wang JH, Swimmer Y, Holland K and others (2012) The effects of a lanthanide metal alloy on shark catch rates. *Fish Res* 131–133:45–51
- IATTC (Inter-American Tropical Tuna Commission) (2019) Joint t-RFMO FAD Working Group 2nd Meeting, 8–10 May 2019, San Diego, CA. https://www.iattc.org/Meetings/Meetings2019/SAC-10/OTM-33/Docs/_English/OTM-33-RPT_2nd%20Meeting%20of%20the%20Joint

- %20Tuna%20RFMOs%20Working%20Group%20on%20FADs.pdf
- ISSF (International Seafood Sustainability Foundation) (2010) Bycatch reduction: setting a new course and speed for bycatch reduction in tuna purse seine FAD fishing. ISSF, McLean, VA
- ISSF (2012) KOBE III Bycatch Joint Technical Working Group: harmonisation of purse seine data collected by tuna—RFMO observer programmes. ISSF Tech Rep 2012-12
- ISSF (2016) Compendium of ISSF at-sea bycatch mitigation research activities as of July, 2016. ISSF Tech Rep 2016-13.12th Working Party on Ecosystems and Bycatch (WPEB12), Indian Ocean Tuna Commission (IOTC). IOTC-2016-WPEB12-INF05
- ISSF (2019) Non-entangling and biodegradable FADs guide. <https://issf-foundation.org/knowledge-tools/guides-best-practices/non-entangling-fads/download-info/non-entangling-and-biodegradable-fads-guide-english/>
- Jiménez S, Domingo A, Abreu M, Forselledo R, Pons M (2013) Effect of reduced distance between the hook and weight in pelagic longline branchlines on seabird attack and bycatch rates and on the catch of target species. SBWG5 Doc 49. Fifth Meeting of the Seabird Bycatch Working Group, La Rochelle, 1–3 May 2013. Agreement on the Conservation of Albatrosses and Petrels (ACAP)
- ✦ Jordan LK, Mandelman JW, McComb DM, Fordham SV, Carlson JK, Werner TB (2013) Linking sensory biology and fisheries bycatch reduction in elasmobranch fishes: a review with new directions for research. *Conserv Physiol* 1:cot002
- ✦ Kaplan I, Cox SP, Kitchell J (2007) Circle hooks for Pacific longliners: not a panacea for marlin and shark bycatch, but part of the solution. *Trans Am Fish Soc* 136:392–401
- Kelleher K (2005) Discards in the world's marine fisheries: an update. FAO Fish Tech Pap 470. FAO, Rome
- Kerstetter DW, Graves JE (2006) Survival of white marlin (*Tetrapturus albidus*) released from commercial pelagic longline gear in the western North Atlantic. *Fish Bull* 104:434–444
- ✦ Kerstetter DW, Graves JE (2008) Post-release survival of sailfish caught by commercial pelagic longline gear in the southern Gulf of Mexico. *N Am J Fish Manage* 28: 1578–1586
- Kerstetter DW, Luckhurst BE, Prince E, Graves JE (2003) Use of pop-up satellite archival tags to demonstrate survival of blue marlin (*Makaira nigricans*) released from pelagic longline gear. *Fish Bull* 101:939–948
- Kim S, Moon D, An D, Koh, J (2006) Comparison of circle hook and J hook catch rate for target and bycatch species taken in the Korean tuna longline fishery. WCPFC-SC 2-2006/EB-WP-12. Western and Central Pacific Fisheries Commission, Palikir
- Kim S, Moon D, An D, Koh J (2007) Comparison of circle hook and J hook catch rate for target and bycatch species taken in the Korean tuna longline fishery during 2005–2006. WCPFC-SC 3-EB SWG/WP-11. Western and Central Pacific Fisheries Commission, Palikir
- Kiyota M, Yokota K, Nobetsu T, Minami H, Nakano H (2004) Assessment of mitigation measures to reduce interactions between sea turtles and longline fishery. Proc Int Symp on SEASTAR2000 and Biologging Science (5th SEASTAR 2000 Workshop), p 24–29. <http://hdl.handle.net/2433/44099>
- ✦ Klaer N, Polacheck T (1998) The influence of environmental factors and mitigation measures on by-catch rates of seabirds by Japanese longline fishing vessels in the Australian region. *Emu* 98:305–316
- ✦ Kobayashi DR, Polovina JJ, Parker DM, Kaezaki N and others (2008) Pelagic habitat characterization of loggerhead sea turtles, *Caretta caretta*, in the North Pacific Ocean (1997–2006): insights from satellite tag tracking and remotely sensed data. *J Exp Mar Biol Ecol* 356:96–114
- ✦ Lewison RL, Freeman SA, Crowder LB (2004) Quantifying the effects of fisheries on threatened species: the impact of pelagic longlines on loggerhead and leatherback sea turtles. *Ecol Lett* 7:221–231
- Lohmann KJ, Wang JH (2006) Behavioral responses of sea turtles to prototype experimental lightsticks. In: Swimmer Y, Wang JH (eds) Sea Turtle and Pelagic Fish Sensory Physiology Workshop, September 12–13, 2006. NOAA Tech Memo NOAA-TM-NMFS-PIFSC-12, p 15–17
- Lohmann KJ, Wang JH, Boles LC, McAlister J, Lohmann CMF, Higgins B (2006) Development of turtle-safe light sticks for use in longline fisheries. In: Swimmer Y, Brill R (eds) Sea turtle and pelagic fish sensory biology: developing techniques to reduce sea turtle bycatch in longline fisheries. NOAA Tech Memo NOAA-TM-NMFS-PIFSC-7, p 65–76
- Lopez J, Ferarios JM, Santiago J, Macarena UO, Moreno G, Murua H (2019) Evaluating potential biodegradable twines for use in the tropical tuna FAD fishery. *Fish Res* 219:105321
- Marsac F, Fonteneau A, Menard F (2000) Drifting FADs used in tuna fisheries: an ecological trap? In: Le Gall JY, Cayre P, Taquet M (eds) Pêche thonière et dispositifs de concentration de poissons. IRD, Laboratoire HEA, Montpellier, p 537–552
- ✦ Martinez-Rincon RO, Ortega-Garcia S, Vaca-Rodriguez JG, Griffiths SP (2015) Development of habitat prediction models to reduce by-catch of sailfish (*Istiophorus platypterus*) within the purse-seine fishery in the eastern Pacific Ocean. *Mar Freshw Res* 66:644–653
- ✦ McLellan WA, Arthur LH, Mallette SD, Thornton SW, McAlarney RJ, Read AJ, Pabst DA (2015) Longline hook testing in the mouths of pelagic odontocetes. *ICES J Mar Sci* 72:1706–1713
- McNamara B, Torres L, Kaaialii G (1999) Hawaii longline seabird mortality mitigation project. Western Pacific Regional Fishery Management Council (WPRFMC), Honolulu, HI
- McPherson G, Nishida T (2010) An overview of toothed whale depredation mitigation efforts in the Indo-Pacific region. *SPC Fish Newsl (Noumea)* 132:31–36
- Mejuto J, García-Cortés B, Ramos-Cardelle A (2008) Using different hook and bait types in the configuration of the surface longline gear used by the Spanish swordfish (*Xiphias gladius*) fishery in the Atlantic Ocean. *Collect Vol Sci Pap ICCAT* 62:1793–1830
- Melvin EF (2003) Streamer lines to reduce seabird bycatch in longline fisheries. WSG-AS 00-33. Washington Sea Grant Program, Seattle, WA
- Melvin EF, Parrish JK, Dietrich KS, Hamel OS (2001) Solutions to seabird bycatch in Alaska's demersal longline fisheries. Project A/FP-7. WSG-AS 01-01. Washington Sea Grant Program, University of Washington, Seattle, WA
- Melvin EF, Sullivan B, Robertson G, Wienecke B (2004) A review of the effectiveness of streamer lines as a seabird bycatch mitigation technique in longline fisheries and

- CCAMLR streamer line requirements. CCAMLR Sci 11: 189–201
- ✦ Melvin EF, Guy TJ, Reid LB (2013) Reducing seabird bycatch in the South African joint venture tuna fishery using bird-scaring lines, branch line weighting and nighttime setting of hooks. *Fish Res* 147:72–82
- ✦ Melvin EF, Guy TJ, Reid LB (2014) Best practice seabird bycatch mitigation for pelagic longline fisheries targeting tuna and related species. *Fish Res* 149:5–18
- Molina A, Ariz J, Palleres P, Molina R, Deniz S (2005) Project on new FAD designs to avoid entanglement of by-catch species, mainly sea turtles and acoustic selectivity in the Spanish purse seine fishery in the Indian Ocean. 1st Meeting of the Scientific Committee of the Western and Central Pacific Fisheries Commission (WCPFC), 8–19 August 2005, Noumea. *Fish Technol Work Pap* 2
- Moreno CA, Rubilar PS, Marschoff E, Benzaquen L (1996) Factors affecting the incidental mortality of seabirds in the *Dissostichus eleginoides* fishery in the southwest Atlantic (Subarea 48.3, 1995 season). CCAMLR Sci 3: 79–91
- Moreno G, Restrepo V, Dagorn L, Hall M and others (2016) Workshop on the use of biodegradable fish aggregating devices (FAD). ISSF Tech Rep 2016-18A. International Seafood Sustainability Foundation (ISSF), Washington, DC
- Moreno G, Orue B, Restrepo V (2018) Pilot project to test biodegradable ropes at FADs in real fishing conditions in the western Indian Ocean. *Collect Vol Sci Pap ICCAT* 74: 2199–2208
- ✦ Mourato BL, Hazin HG, Wor C, Travassos P, Arfelli CA, Amorim AF, Hazin FHV (2010) Environmental and spatial effects on size distribution of sailfish in the Atlantic Ocean. *Cienc Mar* 36:225–236
- Murua J, Moreno G, Restrepo V (2017) Progress on the adoption of non-entangling drifting fish aggregating devices in tuna purse seine fleets. *Collect Vol Sci Pap ICCAT* 73:958–973
- Musyl MK, Brill RW, Curran DS, Fragoso NM and others (2011) Postrelease survival, vertical and horizontal movements, and thermal habitats of five species of pelagic sharks in the central Pacific Ocean. *Fish Bull* 109:341–368
- NMFS & ASMFC (National Marine Fisheries Service and Atlantic States Marine Fisheries Commission) (2013) Workshop on Sea Turtle and Atlantic Sturgeon Bycatch Reduction in Gillnet Fisheries, Jan 22–23, 2013, Ocean City, MD
- Northridge SP, Hofman RJ (1999) Marine mammal interactions with fisheries. In: Twiss Jr, Reeves RR (eds) Conservation and management of marine mammals. Smithsonian Institution Press, Washington, DC, p 99–119
- ✦ O'Connell CP, Abel DC, Gruber SH, Stroud EM, Rice PH (2011) Response of juvenile lemon sharks, *Negaprion brevirostris*, to a magnetic barrier simulating a beach net. *Ocean Coast Manage* 54:225–230
- ✦ O'Connell CP, Stroud EM, He P (2014) The emerging field of electrosensory and semiochemical shark repellents: mechanisms of detection, overview of past studies, and future directions. *Ocean Coast Manage* 97:2–11
- Ochi D, Sato N, Katsumata N, Guy T, Melvin EF, Minami H (2013) At-sea experiment to evaluate the effectiveness of multiple mitigation measures on pelagic longline operation in western North Pacific. WCPFC-SC9/EB-WP-11. Western and Central Pacific Fisheries Commission (WCPFC)
- Otley HM, Reid TA, Pompert J (2007) Trends in seabird and Patagonian toothfish *Dissostichus eleginoides* longliner interactions in Falkland Island waters, 2002/03 and 2003/04. *Mar Ornithol* 35:47–55
- ✦ Pacheco JC, Kerstetter DW, Hazin FH, Hazin H and others (2011) A comparison of circle hook and J hook performance in a western equatorial Atlantic Ocean pelagic longline fishery. *Fish Res* 107:39–45
- ✦ Parga M, Pons M, Andraka S, Rendon L and others (2015) Hooking locations in sea turtles incidentally captured by artisanal longline fisheries in the Eastern Pacific Ocean. *Fish Res* 164:231–237
- Patterson H, Hansen S, Larcombe J (2014) A review of shark bycatch mitigation in tuna longline fisheries, Canberra, July. WCPFC-SC10-2014/ EB-WP-05. Western and Central Pacific Fisheries Commission (WCPFC), Scientific Committee Tenth Regular Session, Majuro, 6–14 August 2014
- Peatman T, Pilling G (2016) Monte Carlo simulation modeling of purse seine catches of silky and oceanic whitetip sharks. WCPFC-SC12-2016/ EB-WP-03. Western and Central Pacific Fisheries Commission (WCPFC)
- ✦ Piovano S, Swimmer Y, Giacoma C (2009) Are circle hooks effective in reducing incidental captures of loggerhead sea turtles in a Mediterranean longline fishery? *Aquat Conserv* 19:779–785
- ✦ Poisson F, Filmalter JD, Vernet al. Dagorn L (2014) Mortality rate of silky sharks (*Carcharhinus falciformis*) caught in the tropical tuna purse seine fishery in the Indian Ocean. *Can J Fish Aquat Sci* 71:795–798
- Polovina J, Howell E, Parker D, Balazs G (2003) Dive-depth distribution of loggerhead (*Carretta carretta*) and olive ridley (*Lepidochelys olivacea*) sea turtles in the central North Pacific: Might deep longline sets catch fewer turtles? *Fish Bull* 101:189–193
- ✦ Prince ED, Goodyear CP (2006) Hypoxia-based habitat compression of tropical pelagic fishes. *Fish Oceanogr* 15: 451–464
- ✦ Rabearisoa N, Bach P, Tixier P, Guinet C (2012) Pelagic longline fishing trials to shape a mitigation device of the depredation by toothed whales. *J Exp Mar Biol Ecol* 432–433:55–63
- ✦ Read A (2007) Do circle hooks reduce the mortality of sea turtles in pelagic longlines? A review of recent experiments. *Biol Conserv* 135:155–169
- ✦ Reid TA, Sullivan BJ, Pompert J, Enticott JW, Black AD (2004) Seabird mortality associated with Patagonian toothfish (*Dissostichus eleginoides*) longliners in Falkland Islands waters. *Emu* 104:317–325
- Reid E, Sullivan B, Clark J (2010) Mitigation of seabird captures during hauling in CCAMLR longline fisheries. CCAMLR Sci 17:155–162
- Reinhardt JF, Weaver J, Latham PJ, Dell'Apa A and others (2018) Catch rate and at-vessel mortality of circle hooks versus J-hooks in pelagic longline fisheries: a global meta-analysis. *Fish Fish* 19:413–430
- Restrepo V, Dagorn I, Rubio JL (2017) Questions and answers about FADs and bycatch (version 2). ISSF Tech Rep 2014-04. International Seafood Sustainability Foundation (ISSF), Washington, DC
- Restrepo V, Koehler H, Moreno G, Murua H (2019) Recommended best practices for FAD management in tropical tuna purse seine fisheries. ISSF Tech Rep 2019-11. International Seafood Sustainability Foundation, Washington, DC

- Rey JC, Munoz-Chapuli R (1991) Relation between hook depth and fish efficiency in surface longline gear. *Fish Bull* 89:729–732
- Robbins WD, Peddemors VM, Kennelly SJ (2011) Assessment of permanent magnets and electropositive metals to reduce the line-based capture of Galapagos sharks, *Carcharhinus galapagensis*. *Fish Res* 109:100–106
- Robertson G, Candy SG, Wienecke B, Lawton K (2010) Experimental determinations of factors affecting the sink rates of baited hooks to minimize seabird mortality in pelagic longline fisheries. *Aquat Conserv* 20:632–643
- Robertson G, Candy S, Hall S (2013) New branch line weighting regimes to reduce the risk of seabird mortality in pelagic longline fisheries without affecting fish catch. *Aquat Conserv* 23:885–900
- Rueda L, Sagarminaga R, Baez J, Caminas J, Eckert S, Boggs C (2006) Testing mackerel bait as a possible bycatch mitigation measure for the Spanish Mediterranean swordfish longlining fleet. In: Frick M, Panagopoulou A, Rees A, Williams K (compilers) Book of abstracts of the 26th annual symposium on sea turtle biology and conservation. International Sea Turtle Society, Athens
- Ryder CE, Conant TA, Schroeder B (2006) Report of the Marine Turtle Workshop on Longline Post-Interaction Mortality. NOAA Tech Memo NMFS-F/OPR-29
- Sakai H, Hu F, Arimoto T (2001) Basic study on prevention of incidental catch of seabirds in tuna longline. CCSBT-ERS/0111/62. Report to the Fourth Meeting of the Ecologically Related Species Working Group, Commission for the Conservation of Southern Bluefin Tuna (CCSBT)
- Sales G, Giffoni BB, Fiedler FN, Azevedo VG, Kotas JE, Swimmer Y, Bugoni L (2010) Circle hook effectiveness for the mitigation of sea turtle bycatch and capture of target species in a Brazilian pelagic longline fishery. *Aquat Conserv* 20:428–436
- Sánchez A, Belda EJ (2003) Bait loss caused by seabirds on longline fisheries in the northwestern Mediterranean: Is night setting an effective mitigation measure? *Fish Res* 60:99–106
- Santos MN, Coelho R, Fernandez-Carvalho J, Amorim S (2012) Effects of hook and bait on sea turtle catches in an equatorial Atlantic pelagic longline fishery. *Bull Mar Sci* 88:683–701
- Scott GP, Lopez J (2014) The use of FADs in tuna fisheries. IP/B/PECH/IC/2013-123. Policy Department B: Structural and Cohesion Policies: Fisheries, European Parliament. https://www.wcpfc.int/system/files/IPOL-PECH_NT%282014%29514002_EN.pdf
- Serafy JE, Kerstetter DW, Rice PH (2009) Can circle hook use benefit billfishes? *Fish Fish* 10:132–142
- Serafy JE, Cooke SJ, Diaz GA, Graves JE, Hall M, Shivji M, Swimmer Y (2012) Circle hooks in commercial, recreational, and artisanal fisheries: research status and needs for improved conservation and management. *Bull Mar Sci* 88:371–391
- Simpfendorfer CA, Hueter RE, Bergman U, Connett SMH (2002) Results of a fishery-independent survey for pelagic sharks in the western North Atlantic, 1977–1994. *Fish Res* 55:175–192
- Southwood A, Fritsches K, Brill R, Swimmer Y (2008) Sound, chemical, and light detection in sea turtles and pelagic fishes: sensory-based approaches to bycatch reduction in longline fisheries. *Endang Species Res* 5:225–238
- Stelfox M, Balson D, Hudgins J (2014) Olive ridley project: actively fighting ghost nets in the Indian Ocean. *Indian Ocean Turtle Newsl* 19:23–26
- Stokes LW, Hataway D, Epperly SP, Shah AK, Bergmann CE, Watson JW, Higgins BM (2011) Hook ingestion rates in loggerhead sea turtles *Caretta caretta* as a function of animal size, hook size, and bait. *Endang Species Res* 14: 1–11
- Stoner AW, Kaimmer SM (2008) Reducing elasmobranch bycatch: laboratory investigation of rare earth metal and magnetic deterrents with spiny dogfish and Pacific halibut. *Fish Res* 92:162–168
- Sullivan B (2004) Falkland Islands FAO National Plan of Action for reducing incidental catch of seabirds in longline fisheries. Royal Society for the Protection of Birds
- Sullivan B, Reid TA (2002) Seabird interactions/mortality with longliners and trawlers in Falkland Island waters 2001/02. Falklands Conservation, Stanley
- Sullivan B, Kibel P, Robertson G, Kibel B, Goren M, Candy S, Wienecke B (2012) Safe leads for safe heads: safer line weights for pelagic longline fisheries. *Fish Res* 134–136: 125–132
- Sullivan BJ, Kibel B, Kibel P, Yates O and others (2016) Hook Pod: development and at-sea trialing of a 'onestop' mitigation solution for seabird bycatch in pelagic longline fisheries. SBWG7 Inf 06. 7th Meeting of the Seabird Bycatch Working Group, 2–4 May 2016, La Serena. Agreement on the Conservation of Albatrosses and Petrels (ACAP)
- Swimmer Y, Gilman E (2012) Report of the Sea Turtle Longline Fishery Post-release Mortality Workshop, November 15–16, 2011. NOAA Tech Memo NOAA-TM-NMFS-PIFSC-34
- Swimmer Y, Wang JH (2007) 2006 Sea Turtle and Pelagic Fish Sensory Physiology Workshop, September 12–13, 2006. NOAA Tech Memo NMFS-PIFSC-12
- Swimmer Y, Arauz R, McCracken M, McNaughton L and others (2006) Survivorship and dive behavior of olive ridley (*Lepidochelys olivacea*) sea turtles after their release from longline fishing gear off Costa Rica. *Mar Ecol Prog Ser* 323:253–261
- Swimmer Y, Arauz R, Wang J, Suter J, Musyl M, Bolanos A, Lopez A (2010) Comparing the effects of offset and non-offset circle hooks on catch rates of fish and sea turtles in a shallow longline fishery. *Aquat Conserv* 20:445–451
- Swimmer Y, Empey Campora C, McNaughton L, Musyl M, Parga M (2013) Post-release mortality estimates of loggerhead sea turtles (*Caretta caretta*) caught in pelagic longline fisheries based on archived satellite data and hooking location. *Aquat Conserv* 24:498–510
- Swimmer Y, Gutierrez A, Bigelow K, Barceló C and others (2017) Sea turtle bycatch mitigation in US longline fisheries. *Front Mar Sci* 4:260
- Walsh W, Bigelow K, Sender K (2008) Decreases in shark catches and mortality in the Hawaii-based longline fishery as documented by fishery observers. *Mar Coast Fish Dynam Manage Ecosyst Sci* 1:270–292
- Ward P, Myers RA, Blanchard W (2004) Fish lost at sea: the effect of soak time on pelagic longline catches. *Fish Bull* 102:179–195
- Ward P, Lawrence E, Darbyshire R, Hindmarsh S (2008) Large-scale experiment shows that nylon leaders reduce shark bycatch and benefit pelagic longline fishers. *Fish Res* 90:100–108
- Ward P, Epe S, Dreutz D, Lawrence E, Robins C, Sands A (2009) The effects of circle hooks on bycatch and target

- catches in Australia's pelagic longline fishery. *Fish Res* 97:253–262
- ✦ Watson JT, Bigelow K (2014) Trade-offs among catch, bycatch, and landed value in the American Samoa longline fishery. *Conserv Biol* 28:1012–1022
- Watson JW, Foster DG, Epperly S, Shah A (2003) Experiments in the Western Atlantic Northeast distant waters to evaluate sea turtle mitigation measures in the pelagic longline fishery. Report on experiments conducted in 2001 and 2002. NOAA Fisheries, US Department of Commerce
- Watson JW, Foster D, Epperly S, Shah A (2004) Experiments in the western Atlantic Northeast distant waters to evaluate sea turtle mitigation measures in the pelagic longline fishery. Report on experiments conducted in 2001–2003. NOAA Fisheries, US Department of Commerce
- ✦ Watson JW, Foster D, Epperly S, Shah A (2005) Fishing methods to reduce sea turtle mortality associated with pelagic longlines. *Can J Fish Aquat Sci* 62:965–981
- WCPFC (Western and Central Pacific Fisheries Commission) (2013) Summary report of the 9th Regular Session of the Commission. 2–6 December 2012, Manila
- ✦ Weimerskirch H, Capdeville D, Duhamel G (2000) Factors affecting the number and mortality of seabirds attending trawlers and long-liners in the Kerguelen area. *Polar Biol* 23:236–249
- ✦ Werner T, Kraus S, Read A, Zollett E (2006) Fishing techniques to reduce the bycatch of threatened marine animals. *Mar Technol Soc J* 40:50–68
- Wiedenfeld DA, Crawford R, Pott CM (2015) Results of a workshop on reduction of bycatch of seabirds, sea turtles, and sea mammals in gillnets, 21–23 January 2015. American Bird Conservancy and BirdLife International
- Williams PG (1998) Shark and related species catch in tuna fisheries of the tropical Western and Central Pacific Ocean. Prepared for the FAO 23–27 April 1998 Meeting of the Technical Working Group on Sharks. South Pacific Commission, Noumea
- Witzell W (1999) Distribution and relative abundance of sea turtles caught incidentally by the US pelagic longline fleet in the western North Atlantic Ocean, 1992–1995. *Fish Bull* 97:200–211
- WPRFMC (Western Pacific Regional Fishery Management Council) (2019) Report of the Workshop to Review Seabird Bycatch Mitigation Measures for Hawaii's Pelagic Longline Fisheries, September 18–19, 2018. WPRFMC, Honolulu, HI. www.wpcouncil.org/wp-content/uploads/2018/11/WPRFMC_2018-Seabird-bycatch-mgmt-workshop_FinalReport.pdf
- ✦ Yokota K, Minami H, Nobetsu T (2006a) Research on mitigation of the interaction of sea turtle with pelagic longline fishery in the western North Pacific, Part I: sea turtle. *Proc 3rd Int Symp on SEASTAR2000 and Asian Bio-logging Science (7th SEASTAR 2000 workshop)* (2006): 3–8. <http://hdl.handle.net/2433/49734>
- Yokota K, Minami H, Kiyota M (2006b) Measurement-points examination of circle hooks for pelagic longline fishery to evaluate effects of hook design. *Bull Fish Res Agency Jpn* 17:83–102
- ✦ Yokota K, Kiyota M, Okamura H (2009) Effect of bait species and color on sea turtle bycatch and fish catch in a pelagic longline fishery. *Fish Res* 97:53–58
- ✦ Zollett EA, Swimmer Y (2019) Safe handling practices to increase post-capture survival of cetaceans, sea turtles, seabirds, sharks, and billfish in tuna fisheries. *Endang Species Res* 38:115–125

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Honolulu, Hawaii, USA*

*Submitted: December 12, 2019; Accepted: August 20, 2020
Proofs received from author(s): December 8, 2020*