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A review of shark bycatch mitigation in tuna longline fisheries

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Contents

Summary

Sharks are a significant component of the catch species in pelagic longline fisheries that generally target tuna and tuna-like species. They may be a target species in some cases, but are more often a byproduct (incidentally caught but retained) or a bycatch (incidentally caught but unwanted and discarded) species. Incidental catch of sharks in pelagic longline fisheries has raised concerns about the status of shark populations and the need for mitigation measures to reduce mortality. Despite these concerns, progress in research and implementation of bycatch mitigation measures for sharks has lagged behind measures for other bycatch species such as seabirds.

A review of the most studied mitigation methods (generally defined as measures that reduce the incidence of sharks being caught on the gear) is undertaken here and is extended to include measures that reduce mortality once the shark is captured and brought to the boat. While not exhaustive, the review identified the following:

1. The three most promising approaches to mitigating mortality of sharks from pelagic longline are hooks type (circle), leader type (monofilament) and best practice handling at the vessel. From a technical viewpoint we suggest that there is often sufficient information in the literature to allow reasonably informed decisions on reducing shark mortality using these approaches. However, a number of issues have hampered studies of mitigation and make it difficult to form a synthesis:
    a. Lack of statistical power, often due to low sample sizes or the fact that shark bycatch is often a rare event.
    b. Problems with experimental design that lead to confounding between multiple mitigation measures and inability to quantify the effects of all treatments and their combinations (interactions).
    c. Poor coverage of experimental or observer-based research encompassing the main equatorial Pacific fleets that undertake the majority of the WCPO longlining.
2. Quantifying the *magnitude* of likely reduction in mortality from the introduction of a mitigation approach is critical for determining whether proposed approaches are likely to achieve the overall reductions in fishing mortality required to remove overfishing. The following points and recommendations are made for future research and data collection.
    a. There are two main alternative approaches for data collection and both would require some directed fishing:
        i. Observer data at the required minimum levels with appropriate detail in reporting supplemented by directed fishing to fill data gaps.
        ii. Large-scale directed fishing designed to fill research gaps.
    b. Assessment of post-release mortality under different mitigation regimes is a priority. Studies using PSAT tagging that establish a relationship between quantitative measures of animal condition and mortality are most valuable.
    c. Studies of shark interactions with the hook and leader ('bite off', using video technology) are a priority
3. There is a need to better understand the barriers to the uptake of measures that have demonstrated technical efficacy. Research (scientific and economic) on the likely

costs/benefits of changing gear and fishing practices to mitigate shark mortality is required and should address: changes to target species catch rates, loss of economic byproduct, initial costs of gear, ongoing costs of gear and labour. An additional barrier to uptake of measures relates to operational safety issues from deploying modified gear and implementing best practice handling of sharks.

1 Introduction

Sharks (defined here in the general sense to refer to the Class Chondrichthyes, including all species of sharks, skates, rays and chimaeras) are important in global fisheries as both target and byproduct species (incidentally caught but retained). They are also taken as bycatch (incidentally caught but unwanted and discarded). Some exploited shark species can support higher levels of mortality due to their life history characteristics and thus are likely to be at lower risk from fishing mortality (e.g. blue sharks; Kirby 2006; Oldfield et al. 2012) and well-managed and sustainable shark fisheries do exist (e.g. Australian gummy shark [*Mustelus antarcticus*] determined to be not overfished and not subject to overfishing; Woodhams et al. 2013). However, other shark species are not able to sustain high levels of mortality and are subject to high levels of exploitation. As a result, some shark populations are in decline (e.g. Baum et al. 2003; Baum & Myers 2004; Dulvy et al. 2008; Ferretti et al. 2008; Worm et al. 2013; Dulvy et al. 2014) and one quarter of shark and ray species are threatened according the Red List criteria of the International Union for the Conservation of Nature (Dulvy et al. 2014). This high level of mortality has, to some extent, been driven by the demand for shark fins (Clarke et al. 2006, 2007) and often proceeds unregulated, with few limits for shark catches in place leaving certain species at a high risk of overexploitation due to inadequate management (Lack et al. 2014). However, this demand for shark fins has recently decreased, partially due to new spending restrictions implemented by the Chinese government, as well as conservation awareness (Clarke & Dent 2014).

Declining shark populations are especially concerning as sharks are often apex predators and thus may influence marine communities via 'top-down' control (Baum & Worm 2009; Ferretti et al. 2010), although the degree of influence may vary among habitats. Several studies have demonstrated this top-down control and the ecological consequences when it is removed. For example, a long-term study of tiger sharks (*Galeocerdo cuvier*)and their prey in the seagrass system of Shark Bay, Western Australia found that the behaviour of prey species was influenced by the presence of tiger sharks and the risk of predation, with prey species avoiding high-risk predation areas (see Heithaus et al. 2012 and references therein). This risk-averse behaviour also impacted seagrass communities, as high predation risk areas were not grazed by species such as dugongs and turtles and those seagrass communities were thus not structured by foraging (Burkholder et al. 2013).

Similarly, Myers et al. (2007) demonstrated that the overfishing and population decline of the apex sharks in the northwest Atlantic resulted in the release of their mesopredator elasmobranch prey species. These mid-trophic level prey sharks and rays, no longer subject to apex shark predation, increased dramatically in some cases and this had cascading effects. For example, surveys indicated that the cownose ray (*Rhinoptera bonasus*) population increased by an order of magnitude compared to the 1970s. This increase of cownose rays, which primarily feed on bivalves, has been linked to the collapse of the bay scallop fishery in North Carolina because the rays feed on the bivalves prior to spawning. Thus, sharks play important ecological roles and maintaining shark populations is important in order to maintain ecosystem functions.

Oceanic sharks from a variety of taxa are defined as highly migratory species under the United Nations Convention on the Law of the Sea (UNCLOS 1982). In the case of the *Convention on the Conservation and Management of Highly Migratory Fish Stocks in the Western and Central Pacific Ocean* sharks, along with the primary tuna targets, are subject to the convention's objective to ensure long-term conservation and sustainable use. Similarly, the *FAO International Plan of Action for the Conservation and Management of Sharks* was developed to provide steps towards assessing if there is an issue regarding sharks, guidance on shark management and conservation (FAO 1999) and to promote the development and implementation of national plans of action. More recently, "precautionary, science-based conservation and management measures", which are consistent through the Joint Tuna regional fisheries management organisation (RFMO) process (Anon 2009), have been advocated.

Oceanic or pelagic sharks and rays may comprise a high percentage of the catch in pelagic longline fisheries as either target, byproduct or incidental bycatch (e.g. ~25 per cent of the catch; Mandelman et al. 2008) and may be subject to high levels of mortality from fishing (Dulvy et al. 2008). This has led to overfishing of several species of pelagic shark commonly captured on pelagic longlines targeting tuna. Stock assessments of oceanic whitetip and silky shark conducted for the Western and Central Pacific Fisheries Commission (WCPFC) indicated that both species were overfished and subject to overfishing. For oceanic whitetip, the estimated fishing mortality was far in excess of the levels associated with maximum sustainable yield ($F_{CURRENT}$ / F_{MSY} = 6.5; Rice & Harley 2012) and similarly for silky shark ($F_{CURRENT}$ / F_{MSY} = 4.3; Rice & Harley 2013). Findings from these assessments led the WCPFC Scientific Committee to conclude that in order to adequately reduce fishing mortality bycatch mitigation (i.e. capture prevention) measures were needed, in addition to any controls on retaining catch. Stock assessments of pelagic sharks have proven to be challenging because of a lack of information on species biology as well as poor fisheries data (including on catch levels and hence catch per unit effort). Most of the shark species that comprise incidental catch have not been subject to such rigorous quantitative assessment. Risk assessments have raised concerns across a broader suite of sharks in the western and central Pacific Ocean (WCPO; Kirby 2006) and 14 key shark species have been designated by the WCPFC (Clarke 2011; Harley et al. 2013).

Despite the prevalence of shark bycatch in pelagic longline fisheries and the recommendations to establish mitigation measures for sharks, progress in research and implementation of such measures has generally lagged behind measures for other bycatch species such as seabirds. For example, tuna RFMOs have implemented binding, best-practice measures to mitigate seabird bycatch, such as the use of bird scaring lines and/or weighted lines to prevent seabirds from taking baited hooks as they are deployed. However, equivalent best-practice measures for sharks have not yet been agreed in these RFMOs, despite research indicating that some measures are likely to be effective to some degree. This is likely due to the complexity of mitigating shark bycatch because sharks may also be target or profitable byproduct species in some fisheries and mitigation measures for sharks may affect the catch rates of other target species (e.g. tuna).

This lack of implementation is in contrast to the domestic arrangements of some of the member countries of the tuna RFMOs, which have implemented shark-specific measures in some cases. For example, wire leaders are prohibited in the longline tuna fisheries managed by the Australian government because the use of wire leaders is often associated with targeting and retaining sharks and has been demonstrated to increase the catch rate of sharks (e.g. Ward et al. 2008). Shark finning is also prohibited in these fisheries and sharks must be landed with their fins naturally attached to the first point of landing; further trip limits apply limiting the number of sharks that can be taken. Similarly, in 2013 the EU initiated a ban on finning, with all EU vessels worldwide required to land sharks with their fins naturally attached. Shark sanctuaries, where commercial shark fishing is not permitted, have also been established in several countries, including the Cook Island, New Caledonia, Palau, the Maldives, the Marshall Islands and French Polynesia.

Furthermore, a number of sharks species being caught in longline fisheries in the WCPFC are listed in the *Appendices of the Convention on the Conservation of Migratory Species* (UNEP/CMS) and its specialized daughter agreement, the *Memorandum of Understanding on the Conservation of Migratory Sharks* (CMS Shark MOU). Being concerned about the significant mortality of sharks from a range of impacts and threats, including bycatch, Signatories to this MOU have committed themselves through a global Conservation Plan for migratory sharks:

- to develop programs to monitor shark bycatch
- to promote capacity building for safe handling and release of sharks
- to develop and use selective fishing gear, devices and techniques to ensure that the taking of sharks in fisheries is sustainable and appropriately managed and that mortality of non-utilized caches is minimized to the greatest extent possible.

Although some countries have enacted shark-specific measures and there is evidence that some methods are useful or promising, some of the studies on shark mitigation measures have provided contradictory results. Thus, the information required to agree on best-practice methods has been lacking to some degree, and this has contributed to a reluctance of tuna RFMOs to implement shark-specific catch mitigation measures. There is also reluctance because of uncertainty around the potential for economic impacts from mitigation measures through reduced catches of target species or through the costs for new or lost gear and labour. However, noting the known status of the very small number of shark species for which we have reasonably robust assessments, actions to mitigate bycatch and incidental mortality of shark species is a matter of urgency. In addition, where measures have been introduced, a lack of compliance can be an issue (e.g. Clarke 2013), and enforcement of mitigation measures when introduced is a priority.

This paper briefly reviews the current state of knowledge for several major shark mitigation methods for pelagic longline fisheries including circle hooks, deterrents and leader material, as well as handling measures. We note that while a number of gear types may impact shark stocks and that cumulative impact of all gear types ultimately needs to be considered in stock assessments and for potential mitigation measures, here we focus just on pelagic longline. For the purposes of this paper, we extend the term 'mitigation' beyond the definition used by the WCPFC Scientific Committee to include methods that reduce mortality once the shark has been hooked, as well as methods that reduced shark catch and landings. We note that these issues have been reviewed extensively elsewhere (e.g. Godin et al. 2012; Favaro & Coté in press) and it is not our intent to reproduce that work here. We also note that bycatch mitigation and management involves a range of other issues such as identifying indicators, reference points and decision rules that are beyond the scope of this paper (but see Kirby & Ward 2014).

Rather, the intention of this paper is to summarise what we know about these mitigation measures and also what we do not know. In particular, this paper notes the lack of comprehensive mitigation research in the largest tuna fishery in the world, which includes the longline fleets operating in the Convention Area of the WCPFC. By identifying knowledge gaps, directed research can be undertaken and some of these important questions about mitigation of shark species can be addressed in a timely manner to allow the implementation of mitigation measures with quantified effectiveness. However, while further data collection and research would enhance our understanding of mitigation measures and their utility, given the status of some shark stocks it is important to acknowledge that there are mitigation measures that are *likely* to be effective if implemented. Such measures are also identified in this paper. However, as with any multispecies fishery that has limited capacity for species selection, there is a clear challenge in reducing catch of one species subject to excessive fishing mortality while seeking to maintain catches of other target species subject to target fishing mortality, as well as taking issues such as crew safety and costs of implementation into consideration (e.g. Gilman 2011).

2 Mitigation measures

There are a number of mitigation measures that have been researched or implemented to some degree which may be effective for mitigating shark mortality in longline tuna fisheries. These can be grouped into three categories based on their function:

- Avoiding capture – measures that reduce or prevent the capture of the shark (e.g. deterrents)
- Increasing escape – measures that increase the chance the shark will escape the hook (e.g. monofilament leader)
- Increasing survival – measures that increase the chance the shark will survive after getting off the hook or being released (e.g. reduced soak time, circle hooks and handling practices)

Figure 1 is a diagram of pelagic longline fishing from the perspective of factors that influence the ultimate mortality outcome of a shark that has been hooked and then released. It highlights the potentially complex interactions between mitigation approaches that occur through the capture sequence.

In addition to the factors discussed below, we note that there are a number of approaches that can be used to actively target shark, such as fishing depth (surface setting, including the use of “shark lines” [Bromhead et al. 2013]), fishing location and oceanographic conditions along with the range of factors that are typically used for statistical catch rate standardisation for tuna. These are generally not discussed further here but are clearly an important influence on shark catch rates.

Avoiding capture

This type of mitigation measure seeks to prevent the shark from interacting with the gear and being hooked. There has been substantial recent work on various types of deterrents to repel the shark and prevent it from being hooked and this technique is discussed in detail below. Additional examples of measures to avoid capture not discussed in this report include area closures where fishing is not permitted or move on provisions following interactions.

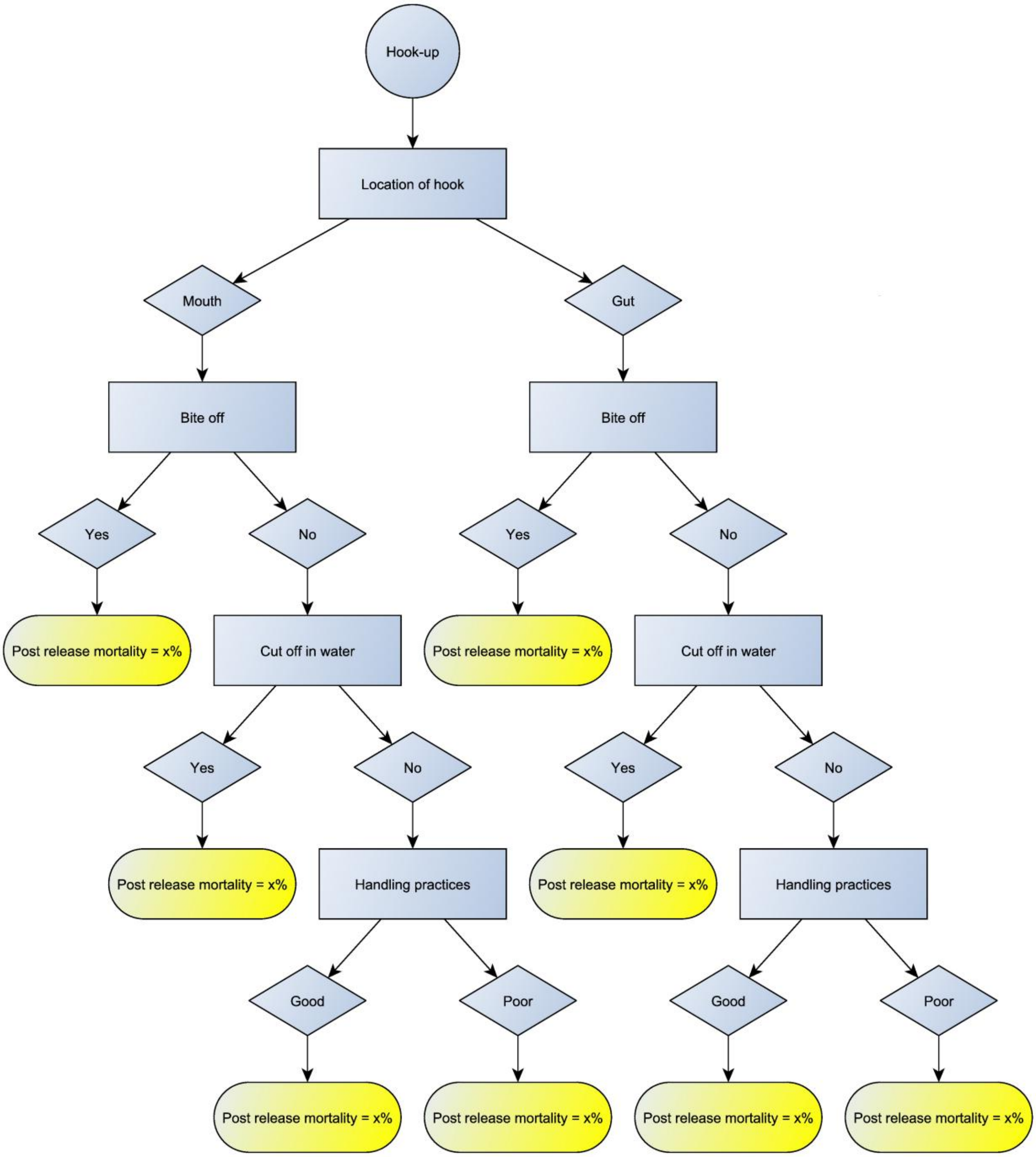
Deterrents

Research into deterrents has focused primarily on those that exploit the fact that elasmobranchs are able to sense electric fields through specialised organs (the ampullae of Lorenzini). These are typically located on the head region of sharks and can detect weak voltage gradients in the range typically produced by prey species (Kalmijn 1971, 1982; Kajiura & Holland 2002). However, as most teleost fishes do not possess the electrosensory organ, the presumed target species should not be affected by the deterrents.

Recent research into shark deterrents has focused on the use of electropositive metals, particularly rare earth elements, which shed electrons in seawater and react with the electronegative skin of the shark to create an electrical field which may then deter the shark from further approaching and interacting with the gear (O’Connell et al. in press). In addition, permanent magnets have also been trialled, including magnets comprised of rare earth elements. The mechanisms through which sharks detect magnetic fields are complex, but the basic premise of using magnets as a deterrent for sharks is that the magnetic field produced is much greater than the geomagnetic field of the Earth and therefore the senses of the approaching shark are overwhelmed and the shark repelled (see O'Connell et al. in press).

Results from studies trialling the use of rare earth elements have been mixed. For example, Stoner & Kaimmer (2008) found that cerium mischmetal was a useful deterrent for spiny dogfish (*Squalus acanthius*), resulting in a reduced catch of 19 per cent in the field test conducted in Alaska. However, this reduction was much less than in the laboratory trial (Kaimmer & Stoner 2008). Similarly, Brill et al. (2009) found that using a mixture of lanthanide elements in a longline trial resulted in a reduction in the catch of sandbar sharks (*Carcharhinus plumbeus*) of ~62 per cent.

Figure 1 Flowchart depicting the mortality associated with the hooking and release of sharks in a longline fishery and factors that influence that mortality.



However, there have been several studies that have not found any significant difference in catch when electropositive metals were used. For example, Tallack & Mandelman (2009) found no effect of cerium mischmetal on the catch of spiny dogfish in the Gulf of Maine. Similarly, Godin et al. (2013) found no effect of electropositive metals on the catch of blue sharks and other shark species in the northwest Atlantic Ocean. McCutcheon & Kajiura (2013) found that there was no effect of the rare earth element neodymium on juvenile lemon sharks (*Negaprion brevirostris*) nor for bonnethead sharks (*Sphyrna tiburo*) when tested both in groups and individually.

There have also been conflicting results for rare earth element magnets. For example, Stoner & Kaimmer (2008) tested rare earth magnets (neodymium-iron-boride) in their laboratory study but found that while the behaviour of the spiny dogfish suggested they can detect the magnetic field, it did not deter them from attacking the bait. This is in contrast to the study of Robbins et al. (2011), who found that neodymium-iron-boride magnets were the only deterrent to produce a significant result when deployed in certain configurations.

In addition, several studies have identified factors that affect the efficacy of deterrents in repelling sharks. For example, Robbins et al. (2011) found that, in the case of Galapagos sharks (*Carcharhinus galapagensis*), high densities reduced the effectiveness of deterrents, with the mean time to take the baits decreasing as the number of sharks increased. Thus, conspecific density may play an important role in determining the effectiveness of the deterrent. Similarly, Jordan et al. (2011) found differences between the responses of two species of shark to neodymium, as well as a difference in the response within a species when competition was introduced (e.g. tested with groups of conspecifics).

This raises another issue that has been noted by researchers, which is the effect of different deterrents on different shark or ray species. For example, the field trial of Kaimmer & Stoner (2008) found that longnose skate (*Raja rhina*) catches were reduced by 46 per cent when cerium mischmetal was used. However, while Brill et al. (2009) found a substantial reduction in the catch of sandbar shark when using a lanthanide alloy, there was no impact on the catch of clearnose skates (*Raja eglanteria*). Hutchinson et al. (2012) tested the effect of a rare earth alloy on catch rates of a suite of shark species in different regions of the Pacific. They found that while catch of juvenile scalloped hammerheads (*Sphyrna lewini*) significantly declined in Hawaii using the alloy, no decline was noted for sandbar sharks in the same region, nor for any species of shark in the other regions (southern California and Ecuador).

Thus, while electropositive metals and magnets have proven to be effective for some species in some studies, there are clearly inter-specific differences in the effect of these deterrents which are yet to be explored. Mitigating factors like the presence of conspecifics may reduce the efficacy of the deterrent in some species. In addition, the expense and need to continually replace electropositive deterrents (as they dissolve in seawater) will likely make them a less desirable and potential unviable option for industry to implement when compared to other potential mitigation methods.

Increasing escape

Leader material

Several studies have examined the effect of leader material on shark bycatch rates. Ward et al. (2008) compared nylon monofilament and wire leaders in a pelagic longline fishery off north-eastern Australia. They found that there was a significantly lower catch of sharks using nylon leaders, likely because sharks were able to bite through the nylon and escape, whereas they could not bite through the wire leaders. Similarly, the catch rate of teleosts with sharp teeth, such as snake mackerel, was significantly less on nylon leaders. In this study, there was no significant difference in catch rates for tuna and tuna-like species, except for bigeye tuna, which had a higher catch rate on nylon than on wire leaders, possibly because the fish could see and avoid the wire leaders.

Similarly, Vega & Licandeo (2009) compared American and Spanish longline systems; the American system used monofilament for the mainline and branch line while the Spanish system used multifilament for the mainline and branch line and also used a wire leader (among other differences between the systems). The study determined that shark catch rates were higher using the Spanish system (4.7 sharks/1000 hooks vs. 2.5 sharks/1000 hooks). There was also a significantly higher catch of blue sharks using the Spanish system. A similar result was found by Marín et al. (1998), who also compared the catches using the American (or Florida) and Spanish longline systems (on single vessels). The authors noted that because the Spanish system uses wire leaders, sharks are prevented from biting off. Indeed, they further noted that 10 per cent of hooks were lost in the American system, and that the American gear system caught fewer large sharks than the system utilising wire.

However, several studies have noted that higher catch rates for sharks were not observed for wire leaders. For example, Branstetter & Musick (1993) found lower shark catch rates with wire leaders in oceanic waters, while in coastal waters (<100 m depth) the catch rate of sharks was higher on monofilament. Berkley & Campos (1988) found fewer shark catches using wire leaders, although they noted a loss of ~5 hooks/100 on monofilament leaders, and suggested that bite offs were likely caused by sharks. It is worth noting, however, that neither of these studies was specifically designed to test differences in catchability between wire and monofilament leaders and the results may therefore be confounded by other factors. Alternatively, in some cases the wire leader may be more visible and thus may be avoided.

Afonso et al. (2012) compared shark bycatch using nylon monofilament and wire leaders, as well as circle and J-hooks. They recorded an increase in bigeye tuna catch when using monofilament leaders. In contrast, catch rates were higher for sharks as a whole, and for blue sharks specifically, when wire leaders were used. However, this study noted that shark bycatch rates on monofilament may be underestimated, as may mortality rates, as the fate of the sharks that have bitten off the line is unknown. If standard J-hooks are used, they may result in a high post-capture mortality rate depending on hooking position (see Figure 1 and section on circle hooks).

Although expensive and difficult to undertake, further research on post-capture survival will be important to evaluate the overall utility of nylon monofilaments, as well as the impact of combining nylon leaders with circle hooks. However, even without such data available, the studies highlighted above indicate that wire leaders result in increased shark capture (Table 1).

Increasing survival

Some mitigation measures serve to reduce mortality rates after the shark has been hooked. The most well researched method in this category is circle hooks, which were designed to reduce the physical damage hooking does. In addition, methods such as handling practices and the soak time, or amount of time between the setting and hauling (i.e. retrieving) of the longline can also have an impact on post-capture survival. Such measures, that may improve the chances of survival once the shark has escaped or been released, are a critical aspect in the reduction of total fishing mortality.

Circle hooks

Early research into the implementation of circle hooks as a mitigation measure was driven largely by the desire to reduce the impacts of longline fishing on sea turtles (e.g. Watson et al. 2005) and of recreational catch-and-release fisheries (e.g. Cooke & Suski 2004). However, the implementation of circle hooks, combined with catch-and-release handling practices, may also lead to reductions in mortality rates of sharks in commercial fisheries (e.g. Kaplan et al. 2007). Circle hooks may also affect the catch rate of sharks.

Table 1 Summary of selected studies on the catchability of sharks and target species using monofilament leaders. Sample sizes are provided in parentheses. An outcome of '↑ on nylon' indicates a statistically significant increase in catch rate using monofilament leaders, while an outcome of '↑ on wire' indicates that catch rate was significantly higher using wire leaders. An outcome of neutral indicates no significant result.

Catch rate		
Species	**Outcome**	**References**
Prionace glauca	↑ on nylon	-
	Neutral	Vega & Licandeo 2009 (145)
	↑ on wire	Afonso et al. 2012 (77)
Carcharhinus falciformis	↑ on nylon	-
	Neutral	Ward et al. 2008 (32)
	↑ on wire	-
Carcharhinus longimanus	↑ on nylon	-
	Neutral	Ward et al. 2008 (14)-Small sample size
	↑ on wire	-
Isurus oxyrinchus	↑ on nylon	-
	Neutral	-
	↑ on wire	Vega & Licandeo 2009 (100)
Sharks grouped	↑ on nylon	-
	Neutral	-
	↑ on wire	Afonso et al. 2012 (182); Vega & Licandeo 2009 (272); Ward et al. 2008 (44)
Target species	↑ on nylon	Ward et al. 2008 (BET [441]); Vega & Licandeo 2009 (ALB [24], BET [44), SWO [747]); Afonso et al. 2012 (BET [104])
	Neutral	Ward et al. 2008 (ALB [282], YFT [1686], SWO[39])
	↑ on wire	-

Albacore = ALB; Bigeye tuna = BET; Yellowfin tuna = YFT; Swordfish = SWO

Circle hooks are designed to increase the likelihood of hooking a fish in the mouth or jaw, rather than in the gut or oesophagus, and thus to promote easy hook removal and to limit injury (Cooke & Suski 2004). The performance of circle hooks varies greatly among species, largely due to different mouth morphologies and feeding methods (Cooke & Suski 2004). Additionally variations in size or design of circle hooks can influence the catchability and survivability of catch (Cooke & Suski 2004; Kerstetter & Graves 2006). We note also the lack of an industry wide standard for size and shape amongst hook manufacturers. These differences may explain the wide variation in the results of studies examining the efficacy of circle hooks and their impact on shark bycatch and can make it difficult to compare studies directly.

For sharks, circle hooks may improve the survivability of encounters as there is a demonstrated association between hooking location and severity of injury to sharks (Campana et al. 2009a; Pacheco et al. 2011; Godin et al. 2012). For example, Campana et al. (2009a) showed that deep-, or gut-hooking, lead to severe injury or mortality in 96 per cent of the sharks examined, while only 3 per cent of mouth-, or jaw-hooked sharks were severely injured or dead at time of haulback.

Despite the intended increase in the rate of jaw hooking, results vary widely when the anatomical location of hooking is examined. Kerstetter & Graves (2006) found that blue sharks (*Prionace glauca*) were hooked internally 26 per cent of the time on both circle and J-hooks, while a study of target and bycatch species in the Australian pelagic longline fishery found that most animals were hooked in the lip or jaw independent of hook type (Ward et al. 2009). However Ward et al. (2009) also found that a higher proportion of silky sharks (*Carcharhinus falciformis*) were jaw hooked when caught on circle hooks, although this result was only marginally significant and the sample size was low (16 silky sharks). Similarly, Promjinda et al. (2008) found that rates of gut hooking in silky sharks declined when circle hooks were deployed, however this finding was also based on a small sample of sharks (10 silky sharks). Afonso et al. (2011) demonstrated that gut-hooking was significantly less frequent when circle hooks were employed in bottom and pelagic longline fisheries off northeast Brazil. While there was a general trend for all ten of the study species, this difference was statistically significant for four species: silky shark, blue shark, night shark (*C. signatus*) and oceanic whitetip (*C. longimanus*). Despite a lack of clear consensus on the efficacy of circle hooks, there does not appear to be a detrimental effect on hooking location associated with circle hooks, with no studies showing *increased* gut-, or foul-, hooking to be associated with circle hooks. However, interactions between hook type and leader type have been noted. For example, Ward et al. (2008) noted that the combination of J-hooks and nylon leaders resulted in more bite offs than when circle hooks were used, due to gut hooking with the J-hooks.

There have been mixed results in studies that assess the influence of circle hooks on the survival rate of bycatch species (Table 2; Serafy et al. 2012). However, it is difficult to compare studies directly due to factors such as small sample sizes that lead to conflicting results, or resulting in no statistical significance or clear conclusions (Godin et al. 2012). For example, several studies have demonstrated that circle hooks have no impact on the survival rate of blue sharks (Yokota et al. 2006; Ward et al. 2009; Serafy et al. 2012), while other studies have shown that the mortality rates of blue sharks declined when circle hooks were used (Campana et al. 2009a; Carruthers et al. 2009; Afonso et al. 2011; Epperly et al. 2012). Afonso et al. (2011) also indicated that circle hooks may reduce the mortality rates of silky and oceanic whitetip sharks, although this study was based on a small sample size and will need to be expanded upon before sound statistical conclusions can be made. It must be further noted that many of these studies assess condition at haulback, and do not account for post-release mortality where the effect of mouth- versus gut-hooking may again manifest.

Despite assumptions that post-release mortality leads to underestimations of true mortality levels, there have been few studies that assesses the post-release survival of sharks, nor has the impact of different hook types on post-release survival been specifically examined (Coggins et al. 2007; Molina & Cooke 2012). Such studies are often challenging due to high levels of associated costs and difficulties in implementation. Musyl et al. (2011) attached pop-up satellite archival tags (PSATs) to five species of pelagic shark (blue sharks, bigeye threshers [*Alopias* *superciliosus*], oceanic whitetip sharks, shortfin makos [*Isurus oxyrinchus*] and silky sharks) caught on commercial longline gear in the central Pacific Ocean to examine post-release survival. They found that post-release survival was high, and documented only a single case of post-release mortality (a male blue shark) during the study. Another study of post-release survival in blue sharks indicated that all sharks considered 'healthy' at time of release survived for the length of the study (a week post-release), while 33 per cent of sharks considered 'badly injured' or 'gut hooked' subsequently died (Campana et al. 2009a). More recently, both the lethal and sub-lethal outcomes of fishing stress were examined in five sympatric shark species (great hammerhead [*Sphryna mokarran*], blacktip shark [*Carcharhinus limbatus*], bull shark [*Carcharhinus leucas*], lemon shark [*Negaprion breviostris*] and tiger shark; Gallagher 2014). This study identified species-specific differences in the effects of fishing stress, with some species being significantly more sensitive than others. It further identified size as a key determinant in both sub-lethal and lethal effects, with larger sharks more able to recover than smaller individuals (Gallagher et al. 2014). These studies demonstrate that sharks can be resilient to capture, and improvements in conditions during handling can have significant impacts on long-term survival. However, none of these studies specifically assessed the effect of circle hooks on post-release mortality, despite the implementation of circle hooks (due to Hawaiian regulations) in the latter part of the Musyl et al. (2011) study and the fact that Gallagher et al. (2014) used circle hooks, albeit attached to drum lines.

Table 2 Summary of selected studies on the survival rate of sharks and target species using circle hooks. Sample sizes are provided in parentheses. An outcome of '↑ on circle' indicates a statistically significant increase in survival rate at haulback (i.e. when the longline is retrieved) using circle hooks, while an outcome of '↑ on J-hook' indicates that survival rate was significantly higher using traditional tuna, or J-hooks. An outcome of neutral indicates no significant result. Studies were labelled as having limited statistical power due to a range of factors such as low sample size or confounding factors.

Survival rate (at haulback):		
Species	**Outcome**	**References**
Prionace glauca	↑ on circle	Campana et al. 2009a (12 404); Carruthers et al. 2009 (10 549); Afosno et al. 2011 (32); Epperly et al. 2012 (21 684)
	Neutral	Yokota et al. 2006 (3353); Kerstetter et al. 2007 (53); Ward et al. 2009 [89]; Serafy et al. 2012 (10 977); Curran & Bigelow 2011 (8895)
	↑ on J-hook	-
	Limited power	-
Carcharhinus falciformis	↑ on circle	Serafy et al. 2012 (2071)
	Neutral	-
	↑ on J-hook	-
	Limited power	Afonso et al. 2011 (12)
Carcharhinus longimanus	↑ on circle	-
	Neutral	-
	↑ on J-hook	-
	Limited power	Afonso et al. 2011 (12)

Survival rate (at haulback):

Species	**Outcome**	**References**
Isurus oxyrinchus	↑ on circle	-
	Neutral	Carruthers et al. 2009 (1189); Epperly et al. 2012 (543)
	↑ on J-hook	-
	Limited power	-
Sphyrna lewini	↑ on circle	-
	Neutral	-
	↑ on J-hook	-
	Limited power	Afonso et al. 2011 (11)
Target species	↑ on circle	Kerstetter et al. 2007 (BET [153]); Carruthers et al. 2009 (YFT [5849], SWO [8479]); Epperly et al 2012 (BET [1719], SWO [16 191]); Serafy et al 2012 (BET [5881], YFT [19 301], SWO [39 225])
	Neutral	Curran & Bigelow 2011 (ALB [405], BET [11 125], YFT [2552], SWO [397]); Kerstetter & Graves 2006 (YFT [124],SWO [667]); Kerstetter et al. 2007 (YFT [82], SWO [170]); Seafy et al 2012 (ALB [32])
	↑ on J-hook	-
	Limited power	Kerstetter & Graves 2006 (BET [23], ALB [16])

Albacore = ALB; Bigeye tuna = BET; Yellowfin tuna = YFT; Swordfish = SWO

Similar to the studies examining mortality, results from studies examining the effect of circle hook implementation on catch rates of sharks have been mixed (Table 3). A meta-analysis of 23 studies (Godin et al. 2012) indicated that hook type does not have a significant effect on shark catch rates (Kerstetter & Graves 2006; Yokota et al. 2006; Galeana-Villasenor et al. 2008; Promjinda et al. 2008; Galeana-Villasenor et al. 2009; Ward et al. 2009; Pacheco et al. 2011). However, there do appear to be species-specific trends with some studies reporting higher catch rates for specific shark species (Bolten et al. 2005; Watson et al. 2005; Kim et al. 2007; Ward et al. 2009, Sales et al. 2010; Afonso et al. 2011; Pacheco et al. 2011) and others reporting lower rates for specific species (Kim et al. 2006; Gilman et al. 2007; Curran & Bigelow 2011). For example, Afonso et al. (2011) identified a significant increase in the catch rate of elasmobranchs (particularly silky shark, blue shark and oceanic whitetip) attributable to the implementation of circle hooks. The authors suggested, however, that this increase may be mediated by adjusting the position of the hook in the water column, with mid-water sets reducing the bycatch of common demersal species. However, mid-water sets did not reduce the catch rate of all species, and may result in increases in catch rate of aggressive species such as tiger sharks and bull sharks.

Due to their high encounter levels in pelagic longline fisheries, blue sharks have been the most intensively studied shark species caught on longlines. This is of particular importance as they appear to be more susceptible to circle hooks, with higher catch rates attributed to the hook type (Bolten & Bjorndal 2005; Watson et al. 2005; Kim et al. 2007; Carruthers et al. 2009; Sales et al. 2010; Afonso et al. 2011). However, while numerous studies have shown that increases in catch rates (of many species) may be attributable to the implementation of circle hooks, Watson et al. (2005) suggest that this may be confounded. The authors indentified higher catch rates of blue sharks associated with circle hook implementation, but suggested that traditional J-hooks result in greater rates of bite offs (due to gut hooking) and therefore higher levels of escape before detection and recording. The perceived increase in catch rate related to circle hooks may be due to increased rates of jaw-hooking, and lower chance of escape. This impact may be countered as the use of circle hooks will allow for sharks to be released, likely with a higher post-release survival rate than those caught on J-hooks, and further result in higher quality of those that are retained (Watson et al. 2005). The potential for interaction with leader type is again noted here, with gut hooks sharks more likely to bite off and escape with monofilament leader compared with wire leader.

Table 3 Summary of selected studies on the catch rates of sharks and target species using circle hooks. Sample sizes are provided in parentheses. An outcome of '↑ on circle' indicates a statistically significant increase in catch rate using circle hooks, while an outcome of '↑ on J-hook' indicates that catch rate was significantly higher using traditional tuna, or J-hooks. An outcome of neutral indicates no significant result. Studies were labelled as having limited statistical power due to a range of factors including low sample sizes or confounding factors.

Catch rate		
Species	**Outcome**	**References**
Prionace glauca	↑ on circle	Bolten & Bjorndal 2005 (17 893); Watson et al. 2005 (12 755); Carruthers et al. 2009 (10 549); Sales et al. 2010 (3233); Afonso et al. 2011 (32)
	Neutral	Kerstetter & Graves 2006 (62); Yokota et al. 2006 (3353); Kerstetter et al. 2007 (53); Ward et al. 2009 (68); Pacheco et al. 2011 (69)
	↑ on J-hook	Curran & Bigelow 2011 (8895)
	Limited power	Kim et al. 2007 (n=25 across four treatments)
Carcharhinus falciformis	↑ on circle	-
	Neutral	-
	↑ on J-hook	-
	Limited power	Promjinda et al. 2008 (10); Afonso et al 2011 (12); Pacheco et al. 2011 (2); Bromhead et al. 2013
Carcharhinus longimanus	↑ on circle	-
	Neutral	Pacheco et al. 2008 (20)
	↑ on J-hook	-
	Limited power	Yokoto et al. 2006 (1); Kim et al. 2007 (11); Afonso et al. 2011 (12); Ward et al. 2009 (8); Bromhead et al. 2013
Isurus oxyrinchus	↑ on circle	-
	Neutral	Sales et al. 2010
	↑ on J-hook	-
	Limited power	Yokota et al. 2006 (27); Ward et al. 2009 (13); Afonso et al. 2011 (6); Pacheco et al. 2011 (6)

Catch rate		
Species	**Outcome**	**References**
Sphyrna lewini	↑ on circle	-
	Neutral	Sales et al. 2010 (234)
	↑ on J-hook	-
	Limited power	Afonso et al. 2011 (11); Pacheco et al. 2011 (2)
Sharks grouped	↑ on circle	Sales et al. 2010 [*Carcharhinus* spp.] (206)
	Neutral	Favaro & Côté in press
	↑ on J-hook	-
	Limited power	Gilman et al. 2007 [confounded with bait switching]
Target species	↑ on circle	Kertetter et al. 2007 (YFT [82], SWO [170]); Ward et al. 2009 (ALB [249], YFT [88]); Sales et al. 2010 (ALB [517], BET [69], SWO [1548]); Pacheco et al. 2011 (BET [916], SWO [608]);
	Neutral	Kerstetter et al. 2007 (BET [153]); Ward et al. 2009 (BET [77], SWO [238]); Pacheco et al. 2011 (ALB [74], YFT [233]); Sales et al. 2010 (YFT [200])
	↑ on J-hook	-
	Limited power	Promjinda et al. 2008 (YFT [3], SWO [21]); Gilman et al. 2007 [confounded with bait switching]

Albacore = ALB; Bigeye tuna = BET; Yellowfin tuna = YFT; Swordfish = SWO

In contrast, other studies have been unable to detect a difference in catch rate between circle hooks and J-hooks (Kerstetter & Graves 2006; Yokota et al. 2006; Kerstetter et al. 2007; Ward et al. 2009; Pacheco et al. 2011). Yokota et al. (2006) indicated that there was no statistical difference between circle and J-hooks in relation to blue shark catch rate in an expansive study that monitored 48 600 hooks. Similarly, Pacheco et al. (2011) did not find a statistically significant difference in the catch rates of most shark species studied (blue shark, oceanic whitetip, shortfin mako, scalloped hammerhead and silky shark), although they found that crocodile shark (*Psuedocarcharias kamoharai*) had a catch rate on circle hooks twice that of the J-hook catch rate. Further, a study of the deep-set Hawaii-based tuna longline fleet found that blue shark catch rate was 17.1 per cent lower on circle hooks when compared to tuna and J-hooks (Curran & Bigelow 2011).

Soak time

Operational processes of fisheries can also have an impact on shark bycatch and survival rates. For example, Braccini et al. (2012) noted that with increased soak time there was a decrease in the post-capture survival of sharks in gillnets. Similarly, Campana et al. (2009a) noted that soak time was a significant factor contributing to the hooking mortality of blue sharks in the Canadian longline swordfish fishery, with mortality increasing with longer soak times. Whoriskey et al. (2011) found a positive trend for bycatch and soak time for silky and thresher sharks (*Alopias* sp.) in the data from the global mahi mahi (*Coryphaena hippurus*) fishery.

In the longline fisheries in the Pacific Ocean, Ward et al. (2004) noted that blue shark catch rates increased with soak time, although they noted that blue sharks were often alive at haulback. This was in contrast to species such as skipjack tuna (*Katsuwonus pelamis*), where longer soak times resulted in lower catch rates and the animals were usually dead at haulback. The authors proposed that this trend may be the result of scavengers removing dead animals off the line prior to haulback, while animals that were alive (i.e. blue sharks) would not be removed.

Handling practices

Campana et al. (2009b) noted that handling practices may have accounted for differences in estimated blue shark mortality between the Atlantic and Pacific fisheries. They noted that on commercial vessels in the Atlantic fishery, while the sharks are not brought aboard, fishers may remove the hook from jaw-hooked sharks if they are able to, which can lead to trauma and potentially higher mortality rates. This was in contrast to the methods used by Moyes et al. (2006) in the Hawaiian fishery, where sharks were cut free from the line or hook, rather than having it forcefully removed and thus appeared to suffer lower mortality rates (Musyl et al. 2009). Moyes et al. (2006) found that sharks that were in good condition when captured had a high likelihood of surviving in the long term after they were released. Therefore, good handling practices are important and could improve shark survival.

Similarly, Patterson & Tudman (2009) reported that improved handling practices were a general recommendation from an expert panel on shark mortality mitigation for a number of shark species across a range of Australian fisheries. These practices would be relatively easy and inexpensive to implement, accounted for crew safety implications, and were therefore likely to be supported and implemented. Indeed, it was noted that implementing better handling practices for sharks may improve handling practices for target species which may result in a better product that can sell for higher prices (Patterson & Tudman 2009). For longline fisheries, recommended handling practices included leaving the animals in the water if possible (i.e. not bringing them on the deck), cutting the line off close to the hook and minimising the time the shark spends out of the water if it must be brought on deck. It was further noted that small sharks can be fragile and easily injured, and should therefore not be handled roughly. In addition, further research on hooking stress and post-release survival was noted as important and such information should be used to continually improve handling practices. For example, Gallagher et al. (2014) found that some shark species were more vulnerable to hooking stress and post-release mortality as a result (i.e. *S. mokarran*), and thus cutting the line to release those animals as soon as possible may improve their survival.

Conclusions of efficacy of mitigation approaches

Based on the information provided above on potential mitigation measures it is apparent that additional research is needed for some of the methods and that some measures may be difficult to practically implement in commercial fisheries (e.g. deterrents). It seems likely that some of the variable or inconsistent results on the effectiveness of mitigation measures stems from variations in experimental conditions that are not controlled for, or apparent, from studies as they are reported. Additionally, where study sample sizes are small there is low statistical power from which robust conclusions can be drawn.

However, it is also apparent that there are three measures which show the most promise and are likely to be effective to some degree in mitigating shark bycatch in longline fisheries, and that can also practically be implemented in commercial fisheries. These measures are:

- hook type (i.e. circle hooks)
- leader material (i.e. monofilament leaders)
- handling practices (e.g. Patterson & Tudman 2009; Poisson et al. 2012)

These measures have been demonstrated to improve post-release survival of animals by preventing injury (i.e. circle hooks, handling practices) or reducing the time the animals spend on the line (i.e. monofilament leaders, handling practices) and thus are likely to reduce the mortality of a range of shark species. There is a clear need to consider the interactions between these approaches (particularly between hook type and leader type) and how they will contribute to the probability that a hooked shark will survive if it is released.

Therefore, despite gaps in our knowledge of shark mitigation measures, which are discussed in the next section, conservation and management measures prescribing the use of these techniques are likely to have a substantial effect on shark mortality in pelagic longline fisheries, including WCPO silky and ocean whitetip stocks that are subject to overfishing. However, there are some clear outstanding issues around shark mitigation that require attention, including quantifying expected changes in mortality from mitigation (to remove overfishing), quantifying the likely costs and trade-offs of implementation (changes to target catch rates, cost of gear) and operational safety issues. These are discussed further below.

3 Research Gaps

The review of mitigation measures above identified the three most promising approaches to mitigating mortality on sharks from pelagic longline. From a technical viewpoint we suggest that there is sufficient information in the literature to allow reasonably informed decisions on reducing shark mortality using these approaches. This is particularly so for handling practices and in many circumstances the likely consequence of decisions around hook type and leader type can be reasonably deduced in terms of likely direction of the effect (up or down) if not the actual magnitude of the effect (in terms of reduced mortality). However, *quantifying* the likely reduction in mortality from the introduction of a mitigation approach is critical for determining whether proposed measures are likely to achieve the overall reductions in fishing mortality to remove overfishing (in the case of WCPFC oceanic whitetip and silky sharks). As advocated by Clarke (2013) and others, the common currency for assessing mitigation measures should be their likely impact on overall fishing mortality. This issue, and approaches to addressing this research gap, are noted below.

Taking a somewhat broader perspective, the second major research gap relates to barriers to the uptake of technical measures that have demonstrated technical efficacy. This includes research (scientific and economic) on the likely costs/benefits of changing gear and fishing practices to mitigate shark mortality including changes to target species catch rates, loss of economic bycatch, initial costs of gear and ongoing costs of gear and labour. An additional item relates to operational safety issues from deploying modified gear and implementing best practice handling of sharks. This research gap is briefly examined here but deserves a more thorough treatment.

Quantifying the effects of mitigation measures

Statistical power

Low statistical power can be caused by several factors including low sample size and/or small effect sizes (i.e. the degree of difference between two variables such as circle hooks and J-hooks) and is a problem in ecological studies (e.g. Jennions & Møller 2003), as well as other scientific disciplines (e.g. Button et al. 2013). Drawing conclusions from studies with low statistical power, poor controls (including confounding) or where the statistical significance is unclear is ill advised and has the potential to confuse our understanding of the effectiveness of mitigation approaches and ultimately impede the development of a synthesis view. Indeed, some of the studies reviewed in this paper were unable to demonstrate statistical significance or draw robust conclusions about the effectiveness of mitigation measures for sharks because of low statistical power, primarily driven by small sample sizes and by lack of proper controls.

One of the advantages of using fisheries-dependant data, including those derived from onboard observers, is the potential to obtain very large sample sizes and therefore high statistical power. It is noted that the analyst has limited control over sampling (representativeness) and experimental design in these circumstances and this can create difficulties with drawing conclusions around the magnitude of effects as well as their interactions (see further discussion below). For designed experiments a power analysis prior to the start of the experiment is critical to guide the sample size required to detect an effect.

Interactions

The results of some mitigation studies may be confounded because of interactions between multiple mitigations measures. Such interactions may make it difficult to draw any meaningful conclusions from a study and it is therefore important that they be noted and, where possible, avoided in future research. For example, some studies changed hook or bait type during the course of the study (e.g. Gillman et al. 2007; Musyl et al. 2011) which may have had an impact on the results. Afonso et al. (2012) specifically examined mitigation measure interactions (e.g. hook type and leader type), however, the statistical power of the study was low and the results for the interaction term were not significant for all the species tested.

Bromhead et al. (2013) examined the hook types (5) and leader types (2) in the Hawaiian deep set tuna fishery using fishery observer data. Such studies are essentially natural experiments that ideally have a reasonable degree of heterogeneity in fishing practices, with reasonable sample sizes across all treatments, including interaction terms. This allows robust statistical comparisons between all treatments and combinations, noting that the interactions between elements of the gear (such as hooks and leader) are very important to quantifying likely changes in catchability (Afonso et al. 2012). Indeed, Bromhead et al. (2013) found that the models were not able to determine the gear interaction effects for silky and oceanic whitetip sharks because of inadequate heterogeneity in fishing practices within the dataset. This could be addressed by larger sample sizes across more fleets (i.e. better observer coverage across a variety of gear combinations) but there may still be a need for directed fishing to fill in particular data gaps.

Similarly, Afonso et al. (2011) noted a significant increase in the catch rate of sharks with the implementation of circle hooks. Although this increase could be the result of the bite off issue noted by Watson et al. (2005), the authors noted that adjusting the position of the hooks in the water column may mediate this increase as mid-water sets reduced the bycatch of common demersal species (although this was not true for all species). The position of the hooks in the water column is generally not examined in studies of circle hooks. Bromhead et al. (2013) found several other factors to be significantly related to shark catch, including latitude, sea surface temperature, longitude and hooks per float. The impact of such factors should be accounted for, particularly in larger/wider ranging studies (in a similar way that target species catch rates are standardised).

Fleet-specific research gaps

There is currently a paucity of research conducted by fleets active in the WCPFC Convention Area. Indeed, we are only aware of a handful of publically available studies that took place within the WCPFC Convention Area (i.e. Yokota et al. 2006; Kim et al. 2007; Ward et al. 2008, 2009; Curran & Bigelow 2011; Bromhead et al. 2013), and few of the data from these studies are from the main fishing area of the equatorial Pacific Ocean. We also found that most of the very large WCPFC fleets that are catching the majority of the tuna in the equatorial Pacific were not represented in these data sets, or were represented by only a single study (Table 4).

While it is likely that some studies and mitigation methods are applicable to a wide variety of longline fleets, fleet-specific operations may influence the efficacy of some methods through slight variations in gear and fishing practices, differences in locations fished with associated differences in the abundance or behaviours of shark species and habitat variables such as temperature profile and productivity. Therefore, there is a pressing need for shark research on bycatch mitigation approaches that encompass the main equatorial Pacific fleets that undertake the majority of the western and central Pacific Ocean longlining.

Given the expense of conducting large-scale fisheries experiments, analysis of fisheries observer data provides the most promising avenue for addressing research gaps across fleets—provided these observer data are sufficiently detailed and capture the full range of interactions between elements of the gear. However, at present, the observer data collected in the WCPFC longline fisheries are not adequate for most fleets and coverage levels are well below the minimum five per cent requirement (Clarke 2013). Indeed, Bromhead et al. (2013) found that only three fleets met the minimum requirements of coverage and contrast to be included in their analysis. However, even in datasets above this threshold, they were unable to differentiate between the effects of the hook and leader interaction terms.

Table 4 Summary of the top 20 (by catch for 2012) commercial longlining States in the WCPFC Convention Area and relevant, publically available shark mitigation studies completed using data from the longline fleets of those States.

Flag	Catch (t)	WCPO Shark mitigation studies
Japan	50988	Yokota et al. 2006
Chinese Taipei	47290	-
China	44355	Bromhead et al. 2013
Korea	29200	Kim et al. 2007
Indonesia	24874	-
Vietnam	16356	-
Fiji	15106	Bromhead et al. 2013
Vanuatu	12859	Bromhead et al. 2013
United States of America	11485	Curran & Bigelow 2011
French Polynesia	5172	-
Papua New Guinea	4069	-
Cook Islands	3557	-
Australia	3224	Ward et al. 2008, 2009
Samoa	2358	-
New Caledonia	2347	-
Spain	2159	-
Tuvalu	2031	-
Federated States of Micronesia	1386	Bromhead et al. 2013
New Zealand	1108	-
Kiribati	620	-

Source of catch data: *WCPFC tuna fishery yearbook, 2012* (current as of 8 November 2013).

Post-release survival

Research quantifying post-release survival of shark species of concern by gear type is also critical for understanding and mitigating mortality. Such research generally employs PSATs and other tagging technology to track the fate of sharks that are captured and then released. This provides a direct measure of how many sharks die in the hours to weeks following release. These studies (e.g. Campana et al. 2009a; Musyl et al. 2011; Hutchinson et al. 2013; Gallagher et al. 2014) can also provide general guides on which sharks are likely to survive post-release. For example, Campana et al. (2009a) noted that all the blue sharks that looked 'healthy' at the time of release survived for at least a week, while sharks that were obviously injured or gut-hooked had a higher likelihood of dying (33 per cent). While such information is useful, it is not always easily used in predictive models that estimate post-release survival.

Studies that establish a predictive mathematical relationship between quantitative measures of animal condition and the likely fate of the animal following release are very valuable because they may have general applicability for a species. For example, Hutchinson et al. (2013) coupled tagging technology and blood chemistry in their study of the post-release survival of juvenile silky sharks in the WCPO purse-seine fishery. They found that blood pH and lactate were good predictors of mortality after release.

This relationship may allow estimates of post-release survival of longline caught silky sharks under different circumstances provided blood chemistry data were collected at release. The advantage of this approach is the reduced (or eliminated) need for tagging and its considerable costs. Caution is required however, as it is not clear whether blood chemistry would be consistently responsive to the injury that may occur from longline fishing (such as gut hooking and handling at the boat) and at the time of release. Further research in this area has the potential for broad applicability and is particularly relevant given the present non-retention requirement for silky and oceanic whitetip sharks within the WCPFC.

Hooking and bite-off

Many studies use the catch rate of sharks as measured by the specimens that are brought to the vessel. Sharks that bite through the line and escape before being hauled are usually unaccounted for and their hooking location and condition are unknown (e.g. Afonso et al. 2012). As discussed this has raised problems when interpreting catch rates and likely mortality from different hooks types, leader types and the interactions between these. A better understanding of what species (shark or otherwise) are biting off and their condition at bite-off (including hooking location) is needed. Such studies will likely involve video technology.

Approach to collecting data

Observer data

The apparently obvious and cost-effective source of data that could be used to improve our understanding of shark bycatch mitigation is from observers. However, these data are currently not likely to be adequate for determining the effectiveness of longline shark mitigation measures in the WCPO (see Bromhead et al. 2013) and for most fleets and coverage levels are well below the minimum five per cent requirement (Clarke 2013). Even a basic understanding of fishing operations in these fleets is often lacking. For example, it is currently unclear which fleets are using which hook types, leader types and handling practices.

For observer data to be effective for quantifying the effectiveness of longline shark mitigation measures we make the following recommendations:

1) Observer coverage of the WCPFC longline fleets be increased to at least the required minimum five per cent level. The main equatorial longline fleets are of particular priority.

2) The data being recorded by observers (http://www.wcpfc.int/system/files/Table-ROP-data-fields-instructions.pdf) be reviewed and amended to ensure that the fields needed to undertake robust statistical analysis of shark mitigation measures are included. Some of these necessary fields are already included, although some require only very general information which may be poorly suited to statistical analysis (See Appendix 1).

3) Where there is low contrast because of inadequate heterogeneity in fishing practices within the dataset there will be a need for directed fishing, as part of a statistically sound

experimental design, to fill in particular data gaps. The analysis of Bromhead et al. (2013) suggests that, even with increased coverage, the problems of correlative factors and confounding is likely to re-occur even with more complete coverage. The issues raised under *Implementation* below (economics and safety) should be examined during this directed fishing.

Large-scale directed fishing

Large-scale, designed, directed fishing is another approach to quantifying the effectiveness of shark bycatch mitigation approaches because of the freedom to properly design data collection processes to address many of the issues raised earlier regarding statistical power, interactions/confounding and coverage of fleets (both areas and fishing approaches). It is apparent from this review that a continuation of one-off unconnected experiments that are specific to one fleet or country, are of small scale and of limited power, is unlikely to facilitate rapid progress. Research at a large scale could be pursued through a single agency but would more likely operate through a large-scale concerted and coordinated collaboration between WCPFC countries where resources can effectively be pooled and elements of the work program shared. Such a program would be expensive and would require robust data collection and validation but should be seen in the context of the costs of the numerous smaller-scale investigations that may occur in a less coordinated way. Importantly, such an approach also affords the opportunity to undertake the needed research on shark "bite-offs", handling practices, post-release survival, economics and crew safety.

Implementation

Understanding and resolving barriers to the uptake of technical measures that have demonstrated technical efficacy is briefly examined here but deserves a more thorough, and potentially fleet specific, treatment. Gilman (2011) notes the need for fishery specific solutions and involvement of fishing industry in testing of approaches. Gilman also proposes the criteria of efficacy at mitigation, practicality, safety, and economic viability (among others) as most important for assessing and demonstrating optimal approaches.

Costs and economics

Uncertainty over the costs and benefits of implementation may be a substantial barrier to the adoption of mitigation measures. Such costs may include changes to target species catch rates, loss of economic byproduct, initial costs of gear and ongoing costs of gear and labour. Many studies do examine the effect of mitigation on catch rates of target species, however very few studies have taken a more systematic approach and examined likely changes to vessel profitability or economic performance.

Ward et al. (2009) found that while circle hooks cost slightly more at the time than traditional J-hooks, the relatively small cost of implementation of the new gear would be outweighed by a commensurate increase in catch rate of both target species and byproduct species. In addition, while some studies have shown an increase in catch of target species using circle hooks (e.g. Ward et al. 2009; Sales et al. 2010), no study that we are aware of has demonstrated a decrease when using circle hooks.

Safety

There is a necessity to ensure the implementation of mitigation measures does not come at a cost to crew safety (Gilman 2011). For example, line weighting methods developed to reduce seabird interactions with longlines resulted in injuries to crew members due to the fly back of lead weights (e.g. Sullivan et al. 2012). Therefore, the gear had to be re-designed to resolve this crew safety issue. However, to our knowledge there has been little work regarding the safety of fishers relating to the implementation of the mitigation measures discussed here. Carruthers et al. (2011) emphasised the importance of investigating the interactive effects of introducing mitigation measures, suggesting that there is a potential for shortened soak times may lead to increased crew fatigue (and therefore danger) due to shortened rest and recovery time. However, studies that seek to examine and resolve the safety implications of implementing measures such as best practice shark handling techniques or changes to hook or leader type have yet to be carried out and are clearly vital.

4 Conclusions

In summary, this paper has briefly reviewed the main mitigation methods available for sharks. Although there are gaps in our knowledge concerning these techniques, three techniques seem likely to be effective to some degree in reducing the mortality of sharks captured on longlines and should therefore be considered for implementation as a matter of urgency. Such implementation does not preclude the need for further research however, and improved observer coverage and reporting would be the most cost-effective means of gathering data on shark mitigation in the equatorial region of the Pacific Ocean. Alternatively, well-designed and specific research projects might be possible and necessary to answer specific questions. However, given the status of many shark populations, delaying action to reduce mortality is not prudent.

The review identified the following:

1. The three most promising approaches to mitigating mortality of sharks from pelagic longline are hooks type (circle), leader type (monofilament) and best practice handling at the vessel. From a technical viewpoint we suggest that there is often sufficient information in the literature to allow reasonably informed decisions on reducing shark mortality using these approaches. However, a number of issues have hampered studies of mitigation and make it difficult to form a synthesis:
    a. Lack of statistical power, often due to low sample sizes or the fact shark bycatch is often a rare event.
    b. Problems with experimental design that lead to confounding between multiple mitigation measures and inability to quantify the effects of all treatments and their combinations (interactions).
    c. Poor coverage of experimental or observer-based research encompassing the main equatorial Pacific fleets that undertake the majority of the WCPO longlining.
2. Quantifying the *magnitude* of likely reduction in mortality from the introduction of a mitigation approach is critical for determining whether proposed approaches are likely to achieve the overall reductions in fishing mortality required to remove overfishing. The following points and recommendations are made for future research and data collection.
    a. There are two main alternative approaches for data collection and both would require some directed fishing:
        i. Observer data at the required minimum levels with appropriate detail in reporting supplemented by directed fishing to fill data gaps.
        ii. Large-scale directed fishing designed to fill research gaps.
    b. Assessment of post release mortality under different mitigation regimes is a priority. Studies using PSAT tagging that establish a relationship between quantitative measures of animal condition and mortality are most valuable.
    c. Studies of shark interactions with the hook and leader (‘bite off’, using video technology) are a priority
3. There is a need to better understand the barriers to the uptake of measures that have demonstrated technical efficacy. Research (scientific and economic) on the likely costs/benefits of changing gear and fishing practices to mitigate shark mortality is

required and should address: changes to target species catch rates, loss of economic byproduct, initial costs of gear, ongoing costs of gear and labour. An additional item relates to operational safety issues from deploying modified gear and implementing best practice handling of sharks.

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Appendix 1

Recommended fields to be recorded by observers to allow robust statistical analysis of shark mitigation measures. Adapted from the *WCPFC Regional Observer Program Minimum Standard Data Fields & Instructions* (http://www.wcpfc.int/system/files/Table-ROP-data-fields-instructions.pdf):

- shark catch and effort data (to species level where possible): currently only required for designated shark species; would be useful if all shark species that can be identified were included
- number of sharks discarded: discards required to be reported by species, although does not specifically note that all species discarded be recorded; should clearly indicate that all discarded species and their numbers be recorded
- method of release (cut free from the line, de-hooked, landed and thrown back etc): currently not required
- handling techniques used (shark not landed, handled according to guidelines, left for prolonged period on deck etc): currently not required
- life status of sharks (alive and vigorous, sluggish, injured, dead etc): currently required when landed on the deck and when released
- sex of the shark: currently should be recorded if possible, noting it may be difficult
- number of bite offs : currently not required
- hooking location (jaw- or gut-hooked): currently not required and may be difficult to determine for animals not landed
- hook type: currently required but not clearly defined; type of hooks used and percentage of each type used should be explicitly reported
- hook size: currently required but not clearly defined; size of the hooks and brand should be clearly identified
- leader material: currently required but not clearly defined; percentage of leader type if a mixture of leaders are used, leader type should encompass all types (including monofilament, braided and wire)
- longline gear information: (data such as the soak time and the depth being fished by the hooks): currently not required