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Mitigation options for shark bycatch in longline fisheries

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A systematic review of literature addressing methods of reducing shark catch rates on longline fishing gear was conducted using academic publication databases and the Ministry for Primary Industries' publications database. Gear technology as well as operational and environmental variables were evaluated as potential elasmobranch bycatch reduction methods for use in New Zealand commercial longline fisheries.

Twenty candidate shark bycatch reduction methods were identified. The criteria used to assess these methods were weighted toward approaches currently ready for deployment in commercial fisheries. The methods of mitigating shark bycatch that ranked highest in this assessment are already used extensively in New Zealand longline fisheries. These are nylon leaders, large hooks and squid bait. Nylon leaders enable sharks to escape by biting off from fishing gear after capture. The 16/0 hooks commonly used in New Zealand surface longline fisheries have been associated with reduced blue shark (*Prionace glauca*) and pelagic stingray (*Pteroplatytrygon violacea*) catch rates, compared to 14/0 circle hooks and J-hooks respectively. Circle hooks are more often associated with increased shark catch rates, which may be due to increased retention on the line rather than increased total catches. Circle hooks complement the use of nylon leaders by reducing the incidence of gut hooking, which improves the odds of survival for animals that bite off the leader. 17/0 and 18/0 circle hooks are common in surface longline fisheries internationally and it is possible that a shift to these larger hooks could further reduce elasmobranch bycatch by making gear less available to smaller individuals.

Other shark bycatch reduction methods that scored highly in this assessment include a shift in setting depth, the use of weak hooks, eliminating lightsticks, and developing artificial bait. A shift in setting depth holds more promise in bottom longline fisheries than in surface longline fisheries, but the research that lead to this conclusion was conducted outside of New Zealand and addressed species not found in New Zealand waters. Understanding the effect of altering setting depth on local elasmobranch species, target catches and vessel operations would require further investigation.

Weak hooks scored highly because they could be very straightforward to implement, but little peer reviewed information was available regarding their impact on shark catch rates, post release survival, or target catch rates, particularly those of large tuna. Likewise, eliminating lightsticks scored highly largely due to ease of implementation. Despite the significant relationships between shark catches and lightstick use reported in the literature, it is probable that the practical significance of such a measure is not great.

Unlike weak hooks or eliminating lightsticks, artificial baits manufactured from fish processing waste scored highly in this assessment because they have the potential to strongly reduce shark catch rates. However, this approach would require extensive development, including creating new formulae from locally available waste products, conducting field trials, and establishing manufacturing capability.

By condensing and summarising available data on how shark and target species' catch rates are influenced by different operational and environmental parameters, this review makes a large amount of information about shark bycatch mitigation options accessible. The scoring system used to assess those options illustrates how the conclusions presented here were reached. This evidence together with a transparent assessment framework is intended to encourage discussion about future directions for shark bycatch mitigation in New Zealand's longline fisheries.

1. INTRODUCTION

Sharks are heavily represented in fisheries bycatch in New Zealand and internationally (Horn 2004, Ayers et al. 2004, Bonfil 1994, Stevens et al. 2000). While some shark species such as rig (*Mustelus lenticulatus*) and school shark (*Galeorhinus galeus*), are targeted and utilised by some New Zealand fisheries (Francis 1998), low-value, non-target shark catches are common in many New Zealand fisheries.

Two examples of fisheries that take significant shark bycatches are the ling (*Genypterus blacodes*) bottom longline fishery and the tuna surface longline fishery. Spiny dogfish (*Squalus acanthias*) is the second highest volume species in the ling bottom longline fishery (Anderson 2008), and high rates of discarding and under-reporting are common for this species (Manning et al. 2004, Burns & Kerr 2008). Likewise, blue sharks (*Prionace glauca*) are often caught in higher volumes than target species in the tuna surface longline fishery (Griggs & Baird 2013, Francis et al. 2001). Of the three species that make up the primary shark bycatches of the tuna surface longline fishery – blue shark, porbeagle shark (*Lamna nasus*) and shortfin mako (*Isurus oxyrinchus*) – low utilisation is common, although shortfin mako are more likely to be retained for their flesh than the other two species (Francis 2013).

Low-value shark bycatch has the potential to incur operational costs such as reduced fishing efficiency and gear damage (Gilman et al. 2008). Spiny dogfish and blue sharks made up the majority of fin-only landings in New Zealand in the 2012–13 fishing year (MPI 2014a), so it is likely that revenue from finning has helped to offset costs that may be associated with catching these otherwise low value species. This changed in October 2014, when New Zealand introduced a ban on the practice of retaining shark fins while discarding the rest of the animal. Issues such as holding space and ammoniation mean that retaining the whole shark may be unfeasible in many operations, so this change is likely to reduce utilisation of shark bycatch. As well as providing tools for fishers to respond to this regulatory change, effective methods of reducing shark bycatch would support the goals that led to the introduction of the finning ban: ensuring that shark species' fisheries mortality is sustainable, minimising fisheries waste, and meeting best-practice standards for fishing and handling sharks (MPI 2013b).

1.1 Objectives

This review systematically canvases shark bycatch reduction methods investigated in published literature and aims to:

- Summarise existing literature on operational and environmental variables that could influence longline shark catch rates, as well as the development of longline shark bycatch reduction devices (BRDs).
- Critically evaluate existing and developing shark bycatch reduction methods for use in commercial longline fisheries, with emphasis on their effectiveness and practicality.
- Identify bycatch reduction methods with potential for application to NZ longline fisheries.

1.2 Overview

This literature review addresses methods for reducing shark bycatch on commercial longline fishing gear. The term "shark" is used here as a catch-all term for any elasmobranch species – shark, ray or skate. As well as blue sharks, shark species that New Zealand fisheries managers have identified as a priority for bycatch mitigation include short finned mako (*Isurus oxyrinchus*) and porbeagle sharks (MPI 2014a).

Patterson et al. (2014) differentiate between bycatch mitigation methods that reduce shark capture rates, those that facilitate sharks' escape after capture, and those that improve survival rates after release or escape from gear. Here, only methods of reducing capture or facilitating escape were reviewed systematically, and the results for each are presented individually. Accounting for post-release survival was necessary to assess candidate bycatch reduction methods that function by facilitating escape rather than reducing capture. This is addressed in the discussion, where bycatch reduction methods are grouped into two categories, 1) technological interventions in the form of gear modifications aimed at improving gear selectivity (Campbell & Cornwall 2008), and 2) operational interventions in the form of altered fishing practices aimed at avoiding bycatch species' interactions with gear.

2. METHODS

2.1 Defining fisheries and gear of interest

This review focused on longline fisheries deploying either surface or bottom longline gear. Both are comprised of a mainline with many shorter leaders (also called branchlines or gangions) attached, each bearing typically a single, terminal hook. While surface longline gear usually drifts in the upper water column, suspended from buoys, bottom longline gear is located near the seafloor and anchored in place.

Hook types commonly used on longline gear include J-hooks, tuna hooks and circle hooks, any of which can be offset or non-offset (Figure 1).

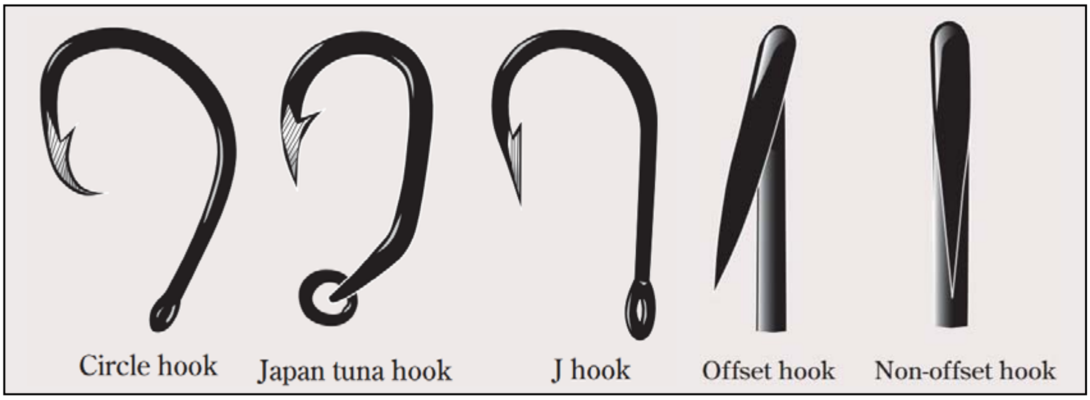

Figure 1: Hook types commonly used in longline fishing gear. Reproduced with permission from Beverly & Park (2009).

2.2 Screening and sorting studies

A systematic search of elasmobranch bycatch reduction methods in the primary literature was carried out by applying the sets of search terms in Appendix 1 to the SCOPUS and MPI publications databases (MPI 2014b). Databases were requested to "sort by relevance" and the first 100–200 results for each new search were screened using the "initial inclusion" criteria in Appendix 1. SCOPUS automatically recommends similar articles when a full text is accessed at the publisher's website and these recommendations were also checked.

Google Scholar and the Scientific Committee publications database of the Western & Central Pacific Fisheries Commission (WCPFC 2014a) were also searched non systematically. Postgraduate theses and further grey literature were searched ad hoc.

"In press" articles were included where relevant. Non-English language studies were excluded from this review. Relevant publications were non-systematically mined for references.

In the initial search phase described above, both the title and abstract of each publication was screened, as well as the contents page if present. If data papers addressed sea turtle catch rates on baited gear but did not mention sharks, the full text was opened and a keyword search for “shark”, “elasmobranch” and “ray” conducted. If these terms were not found, the paper was discarded; if any of these terms was found, the paper was retained. All retained texts were screened secondarily for relevance and quality, and publications that met the following criteria were included in the review:

1. Only data papers were included. Relevant non-data papers, such as reviews, were retrieved and mined non-systematically for references and then excluded.

2. Only papers where the full text was accessible were included.

3. Only studies addressing baited gear or baited apparatus were included. Studies that addressed deterring sharks from a physical location, such as beach net alternatives, were excluded because their results were not directly comparable to a baited gear fisheries scenario.

4. Within each paper, individual results drawn from experiments where equipment failure could jeopardise the reliability of results were excluded. Examples of equipment failure included defining longline gear as bearing an electropositive metal (EPM) treatment even though some EPMs deployed in the field corroded to the extent that they were lost from the hook (Tallack & Mandelman 2009) and electrical failure when deploying an electrosensory deterrent (Gobush & Farry 2012). Laboratory results from Tallack & Mandelman (2009) were included because EPM corrosion was controlled for.

5. Laboratory studies were only included if they did not involve explicitly training captive sharks to exhibit an aversive or non-foraging response to “deterrent” stimuli. For example, Spaet et al. (2010) was excluded because this study involved pairing weak electrosensory stimulus with dropping an inner tube onto the surface of the water above the shark, in an attempt to train an aversive response to electrosensory stimulus. Pals et al. (1982) was also excluded because of deterrent training.

6. Field studies were included if they were conducted as part of a commercial fishing operation, or were intended to simulate the conditions of a commercial fishing operation. Due to high interspecific and regional variation, fisheries-independent field studies that aimed to characterise the distribution or habitat of particular elasmobranch species were excluded *unless* the species addressed features in New Zealand fisheries, as defined in table 2 of the New Zealand NPOA-Sharks (MPI 2013b).

   The exception to this is the inclusion of Stroud et al. (2014), which was conducted in the field, without fishing gear. This study was included because it was part of a very small pool of recent research addressing the use of chemical shark deterrents.

The screening process and the number of studies excluded at each step is presented in the Results section of this review (Figure 2).

2.3 Data extraction

After screening, reported results were then extracted from individual studies. Field studies that employed fishing gear were handled separately from field and laboratory studies that did not.

2.3.1 Field studies employing fishing gear

For a given elasmobranch species, the catch per unit effort (CPUE), total catch, or catchability index on each bycatch reduction method and control was extracted from each study. Following the methods of Godin et al. (2012), results for different species and different bycatch reduction methods from a single study were treated as independent outcomes. CPUE was preferred if multiple indices of catch rate were available. If no table was presented showing change in catch per species on bycatch mitigation treatments and controls, individual species' results were estimated from figures. If neither table nor figure was available, species differences on bycatch mitigation treatments and controls as reported in the text were extracted. When the effect size of a variable was not stated, the direction of the effect was included in qualitative comparisons. Results reported without direction or effect size were excluded.

The relative change from bycatch mitigation treatment to control was calculated, assigned an "increase" or "decrease" value, and the type of statistical test that the authors used to check for significance was noted, along with the presence or absence of a significant difference for that species at the 5% alpha level. This same process was repeated for the following teleost species in surface longline fisheries: bigeye tuna (*Thunnus obesus*), Atlantic bluefin tuna (*Thunnus thynnus*), yellowfin tuna (*Thunnus albacares*), swordfish (*Xiphias gladius*) and mahi mahi (*Coryphaena hippurus*).

Teleost species were selected to reflect impacts of candidate shark bycatch reduction methods on target species, and were not intended to be representative of the range of teleosts taken in New Zealand longline fisheries. Southern bluefin tuna (*Thunnus maccoyii*), rather than Atlantic bluefin, features in New Zealand surface longline fisheries but no results for Southern bluefin were reported in the reviewed studies. Additional teleost species were also chosen from the much smaller volume of results from bottom longline fishing gear.

Results addressing each species were extracted from papers only if they met the following criteria:

1. Ten or more individuals of a given species interacted with the fishing gear or experimental apparatus. Individual results reported in many of the studies were excluded because they did not meet this criterion. Of the data presented by Walker et al. (2005), only results from 1973–76 were included, because for a later dataset it was difficult to ascertain the number of individuals of each shark species caught on longline gear.

2. Relevant fish were identified to genus. Due to the overwhelming evidence that there is great interspecific variation in how catch rate is affected by bycatch reduction methods, pooled results for multiple species were excluded, except for myliobatid rays and mobulid rays. These rays were rarely identified to genus and excluding pooled results would have largely eliminated them from the study.

3. Treatments were not confounded. For example, in Gilman et al. (2007b), bait effects and hook effects cannot be separated. Likewise, the variable "bait" was excluded from the results of Bromhead et al. (2012), as catches on squid and fish baits were pooled. Several individual results presented in Foster et al. (2012) were excluded because bait effect and hook effects were presented together. Results addressing the effect of soak time and fishing by day were excluded from Watson et al. (2005) because fishing by day was confounded with catch volume, as a large catch could push the hauling time past sunrise, while total soak time was confounded with fishing by day, as great total soak times were more likely to include daylight hours. Walsh et al. (2009) was excluded because, for one of their datasets, deep sets tended to use fish bait, while shallow sets tended to use squid bait.

4. Where a modelling result was reported, the direction as well as the significance of a given variable was stated. For example, the significant effect of soak time on swordfish catch rates in Ferreira et al. (2011) was not included because the direction of this effect was not stated. Individual results in Caneco et al. (2014) were excluded when the relationship was described as "significant but complex" without further information to indicate direction or trend. Results from the same study addressing oceanic whitetip (*Carcharhinus longimanus*) catches on wire leaders in the Hawaiian longline fishery were excluded because the effect reported in the text was in conflict with the effect shown in the relevant table.

Some independent variables were also excluded. Wind velocity and frontal energy were both excluded as variables that held little potential for application to bycatch reduction, due to the practical challenges of attempting to define or enforce fishing in "low bycatch" weather. Vega & Licandeo (2009) found that higher wind velocity resulted in shallower set hooks, and it is likely that both wind velocity and frontal energy influence "depth of set", a variable that was included in this review. Field study results relating to water temperature were only included if they specified temperatures rather than simply stating date or season. Due to the complexity of species-specific, sex-specific, ontogenic and seasonal variation in elasmobranch spatial distribution, all spatial variation in catch rate results was excluded from quantitative comparisons. For the same reason, seasonal variation in catch rate results were excluded, but temporal variation on a "day/night" or 24-hour time scale was included.

Some additional results were also excluded due to challenges with interpretation and comparison to other studies' results:

> Results from Bigelow et al. (1999) were only included when the given variable explained at least 1% of the model variance. Results from Bromhead et al. (2012) relating to effects of El Nino/La Nina climatic conditions, thermocline depth and local variability in sea surface temperature (SST) were excluded, as they were likely to interact with the simpler variable that was included, "average SST of fished location".
>
> Pelagic thresher shark (*Alopias superciliosus*) results relating to seamount proximity in Bromhead et al. (2012) were also excluded, due to the complexity of the significant relationship between CPUE and the number of seamounts in the area. Blue shark results from this paper relating to the depth of the water column fished were also excluded for this reason, as were oceanic whitetip shark results relating to lunar cycle.
>
> Results from Ward et al. (2004) were considered qualitatively but were not included in the quantitative comparisons due to difficulties in comparing their random effects coefficient results with other studies "change in CPUE" results.
>
> One result from Hutchinson et al. (2012) was excluded from quantitative reporting. This result was drawn from a catch of only 12 blue sharks and indicated a 166% increase blue shark catch on EPMs compared to controls. If included, this could have influenced the average catch rate beyond the power of the trial. Other results, including one from the same study, addressing blue shark catches on EPMs were drawn from trials where 149 and 156 blue sharks were caught. These latter trials indicated that on average, blue shark catches were 4% lower when EPMs were used. When the result drawn from a catch of only 12 blue sharks in total was included, that average changed to a 38% increase in blue shark catches on EPM treated lines.
>
> "Shark line" and "shark bait" results in Caneco et al. (2014) were excluded, as they indicate that sharks were targeted rather than bycatch.

Any qualitative information deemed relevant to the criteria used to rank candidate bycatch reduction methods' potential for application in New Zealand longline fisheries was also extracted from all papers on an ad hoc basis.

2.3.2 Field and laboratory studies that did not employ fishing gear

In non-fishing gear field studies and laboratory studies of candidate shark deterrent stimuli, the change in shark feeding effort for each candidate bycatch reduction method and control was extracted from each study. Again, results for different species and different bycatch reduction methods from a single study were handled as independent outcomes, as were results from different regions if presented separately. Most studies presented findings in text or graph form rather than a table of results, but if a table was presented showing change in feeding effort per species on bycatch mitigation treatments and controls, the relative change from bycatch mitigation intervention to control was calculated and this result was preferred.

Change in bait consumption was preferred if multiple indices of feeding effort were available. An "increase" or "decrease" value was assigned to results regarding change in feeding behaviour, and the type of statistical test that the authors used to check for significance was noted, along with the presence or absence a significant difference for that species at the 5% alpha level. Findings reported without an effect size or using a metric not comparable to bait consumption were excluded from quantitative comparisons but considered qualitatively. This same process was repeated for any teleost species also tested.

Results addressing each species were extracted from papers if they met the following criteria:

1. Fish (elasmobranch or teleost) were identified to genus.
2. Bait was employed.
3. Trials were replicated for each species.
4. Treatments were not confounded.

Spiny dogfish results in Jordan et al. (2011) were excluded as the data was drawn from a single unreplicated group of animals.

2.4 Synthesis and ranking bycatch reduction methods against criteria

The body of literature addressing research into elasmobranch bycatch reduction methods was expansive and presented highly diverse and often conflicting findings, which made a meaningful narrative summary of the field challenging. A "vote-counting" approach, in which the mode of significant effect sizes is drawn from the literature, was not appropriate because of the large number of contradictory results extracted from the literature (Hedges & Olkin 1980). Instead, average species-specific results were drawn from studies that reported effect size, and reported quantitatively via bar graphs for each bycatch reduction method. The risk in this approach is that effect sizes were not weighted by study power. As a visual estimate of how experimental power varied for the different species reported on, the average total number of treatment and control hooks set was included in each of the effect size graphs used to report on study findings.

Non fishing gear results were also discussed using cross-study average effect sizes, but not graphed.

For both fishing gear and non fishing gear results, the effect sizes per species within each study were calculated by dividing the catch or feeding behaviour metric on treatment baits by the catch metric on control baits, to give the probability of a catch or feeding event on a treatment bait relative to that on a control bait, or risk ratio (Ellis 2010). The risk ratio is referred to as "percent change" in the results.

Each bycatch reduction method in each category was then compared to a set of criteria. A modified version of the criteria proposed by Curran & Bigelow (2011) for a successful bycatch reduction method was used together with an additional "state of development" criterion to assess readiness for immediate use (Table 1). One criterion suggested by Curran and Bigelow but beyond the scope of this review is that the candidate bycatch reduction method should not exacerbate bycatch of other non-target species.

This review addresses methods of reducing shark bycatch, but bycatch reduction research often overlaps with research addressing bycatch mortality and post release survival or bycatch species, which this review did not set out to address. To distinguish between the two fields, any candidate bycatch reduction method that scored a "one" on the first criterion "Method reduces bycatch: bycatch unaffected or increased" was excluded from ranking but considered qualitatively.

In attributing ranking scores for each criteria, results addressing shark species managed in the New Zealand Quota Management System (QMS) were given primary consideration where information was available, as well as thresher sharks (*Alopidae spp.*) which are not listed in the QMS but do feature in New Zealand fisheries bycatch. Results from other species were considered only when there was a paucity of results addressing QMS or New Zealand bycatch species. QMS elasmobranch species are: spiny dogfish, smooth skate (*Dipturus innominatus*), rough skate (*Zearaja nasutus*), school shark, rig (*Mustelus lenticulatus*), mako shark (*Isurus oxyrinchus*), porbeagle shark (*Lamna nasus*) and blue shark.

Table 1: Criteria used to allocate scores and rank shark candidate bycatch reduction methods identified during systematic literature review.

1	**Reduces bycatch**				
Score	1 Bycatch unaffected or increased	2 Bycatch weakly reduced	3 Bycatch moderately reduced	4 Bycatch strongly reduced	5 Bycatch eliminated
2	**Increases fishing efficiency**				
Score	1 Target catches decrease strongly, OR impact on targets unknown	2 Target catches decrease moderately	3 Target catches decrease minimally	4 Target catches unaffected	5 Target catches increase
3	**Requires minimal alteration of normal fishing practices**				
Score	1 Large impact on normal fishing practices	2 Moderate impact on normal fishing practices	3 Minimal impact on normal fishing practices	4 No impact on normal fishing practices	5 Provides operational benefits
4	**Practical for crew to employ and does not increase safety hazards**				
Score	1 Safety hazards might not be resolvable	2 Safety hazards might be isolated	3 Safety hazards might be minimised through training or further development	4 Safety hazards might be eliminated through training or further development	5 No known safety hazards
5	**Feasibly enforced**				
Score	1 Use is reliant on self-reporting		3 Use can be monitored by an observer		5 Use can be monitored from port
6	**State of development**				
Score	1 Has not been applied to fishing gear	2 Limited field trials of prototypes	3 Extensive field trials of prototypes	4 Commercially available, used in some commercial fisheries	5 Commercially available, widespread in commercial fisheries

2.5 Limitations

This review does not account for the "file drawer" problem that is rife in the field of shark electrosensory bycatch reduction, where studies that do not produce significant results go unpublished. This review also does not systematically address unpublished or international grey literature.

This review focuses on average effect size rather than statistical significance as a measure to cope with the wide range of contrasting results presented across many different elasmobranch and target species. Fishing effort has been used in similar studies as a measure of study power (Godin et al. 2012), and fishing effort is presented in effect size graphs here as a visual estimate of study power. Even so, this literature review is not a meta-analysis, as it does not weight mean effect sizes by study power, make quantitative measurements of variability in effect size distribution or conduct statistical tests on effect sizes. What this review does do is identify the scope of candidate shark bycatch reduction methods available for use in longline fisheries, and then use narrative, reporting of average effect sizes and result significance to transparently apply a set of criteria to assess the candidate methods' relative potential for use in New Zealand fisheries.

3. RESULTS

3.1 Search hits

Database searches were conducted between June 15th and August 1st, 2014. 2004 articles were screened initially and 257 progressed to a secondary screening. 63 of those articles met the criteria for inclusion in the review (Figure 2). 56 were field studies that employed fishing gear, 2 were field studies that did not use fishing gear, and 5 were laboratory studies. All studies that did not employ fishing gear investigated either the use of electrosensory or chemical shark deterrents.

Cumulatively, the accessed studies addressed 21 candidate methods of reducing shark catches on longline gear (Figure 3) and results for 50 elasmobranch species were extracted for quantitative comparisons. Blue sharks accounted for 29% of the elasmobranch results, followed by silky sharks (*Carcharhinus falciformis*) (10%), oceanic whitetips (9%), shortfin mako (8%) and pelagic stingray (*Pteroplatytrygon violacea*) (8%).

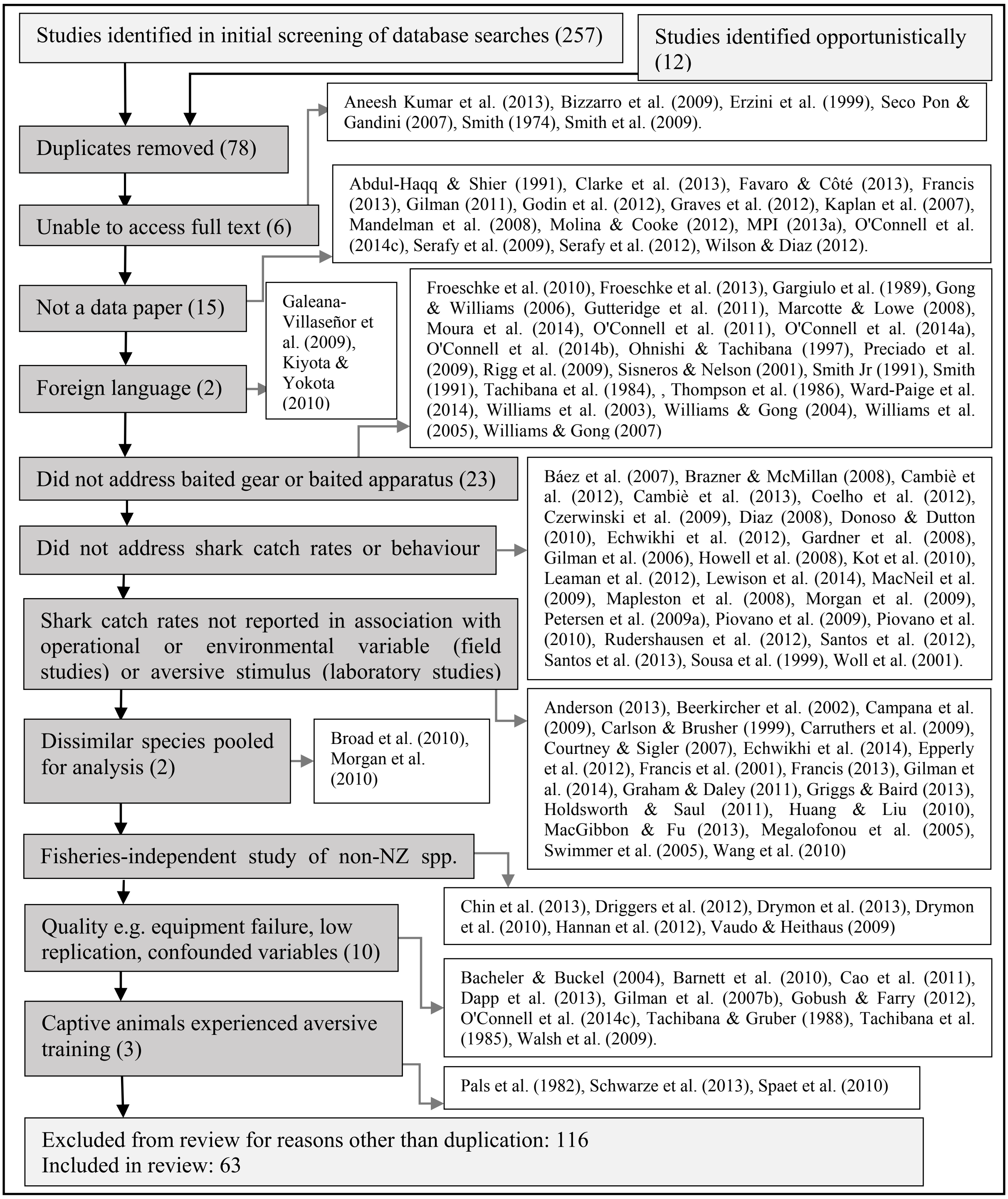

Figure 2: Screening articles for inclusion in quantitative comparison of species specific results.

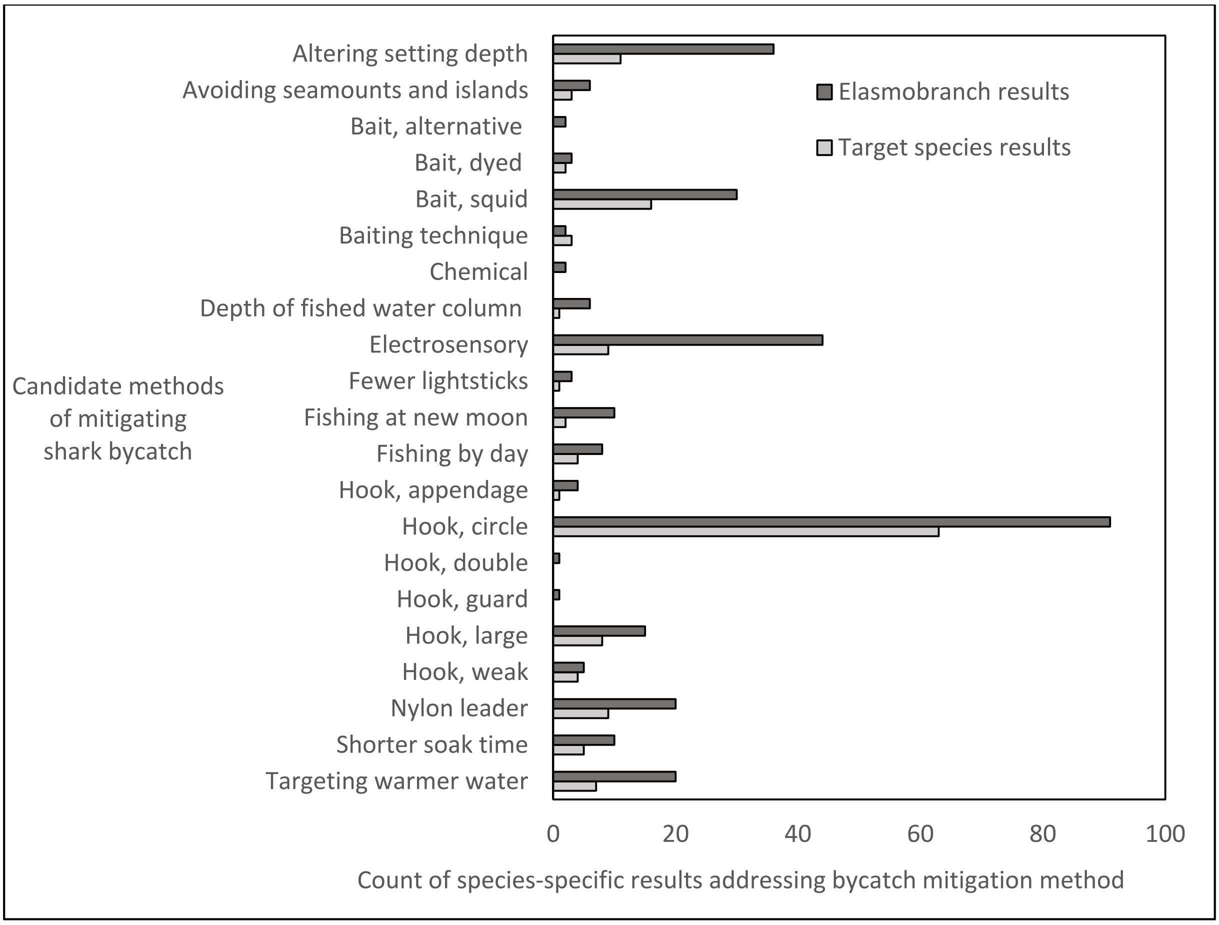

Figure 3: Results extracted from papers included in literature review. Each count refers to one species-specific result reporting the change in catches or feeding behaviour when a candidate bycatch reduction method was used. Most studies trialled multiple bycatch reduction methods on multiple species, generating many individual results per study.

3.2 Candidate bycatch reduction methods

3.2.1 Altering setting depth

Nine studies assessed the impact of gear position in the water column on shark catch rates. A tenth study, Ochi et al. (2013), assessed the impact on line weights on seabird bycatch, considered here because their findings are consistent with line weights affecting setting depth.

Two studies addressed setting bottom longline gear shallower as a bycatch reduction method (Coehlo et al. 2003, Afonso et al. 2011) and the remainder looked at setting depth in pelagic surface longline fisheries. Two studies experimentally manipulated gear depth (Afonso et al. 2011, Beverly et al. 2009), while the majority modelled how the fishing performance of the hooks varied at different depths. Methods of measuring or influencing hook depth included increasing the number of floats used (Afonso et al. 2011), recording the number of hooks between floats (Bromhead et al. 2012), estimating depth based on hook position (Swimmer et al. 2011), or using time-depth recorders (Watson & Bigelow 2014).

Using floats to lift bottom longline gear from the sea floor strongly and significantly reduced southern stingray (*Dasyatis americana*), blacknose shark (*Carcharhinus acronotus*) and nurse shark (*Ginglymostoma cirratum*) catches (Figure 4) (Afonso et al. 2011). In the European hake (*Merluccius merluccius*) bottom longline fishery, the three lowermost hook pairs of hooks on hake bottom longline gear took only 5% of the hake catch, but they caught 16–33% of the three most common elasmobranch bycatch species (blackmouth catshark, *Galeus melastomus*, spotted catshark, *Scyliorhinus canicula*, and smooth lanternshark, (*Etmopterus pusillus*) (Coehlo et al. 2003). The hake caught on these lowest hooks were also significantly smaller than hake caught on hooks higher in the water column.

Results for blue sharks varied widely between studies, but overall shallower hooks on surface longline gear tended to catch more blue sharks. Diurnal migrations mean that the effect of setting depth on blue shark catches probably depends on the time of day (Bromhead et al. 2012). Other species such as silky sharks, shortfin mako and pelagic rays were caught more often on deeper hooks, although the effect of hook depth was highly variable between studies. Watson & Bigelow (2014) estimated that removing the three shallowest hook pairs could reduce blue shark catches by 30%, but this could reflect a reduction in fishing effort rather than an effect of hook depth, because if they modelled reallocating those three hook pairs rather than just removing them, estimated blue shark catches declined by just 5%.

Swordfish and yellowfin tuna catches on surface longline gear were greater on shallow hooks, although not significantly so, while changes in bigeye tuna catches were variable, non-significant and showed an average increase in catches on deeper hooks (Beverly et al. 2009, Watson & Bigelow 2014). Similarly, Ochi et al. (2013) found that bigeye tuna catches increased when lines were weighted, while swordfish catches decreased.

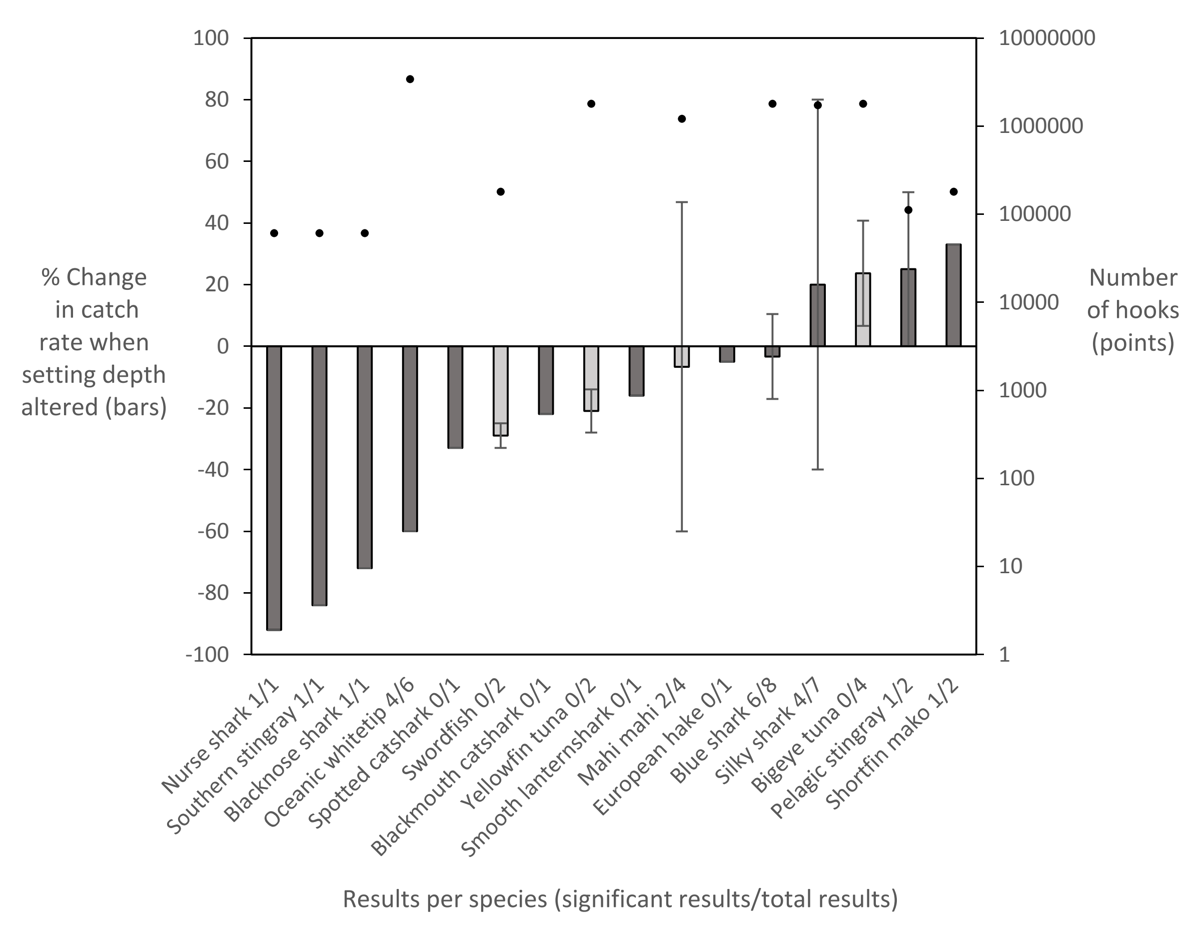

Figure 4: Average percentage change in elasmobranch and teleost catch rates when gear is set deeper (surface longline) or shallower (bottom longline), extracted from studies that stated effect size. Standard error bars shown. Fractions following species names represent the number of significant results over the total number of results for that species, including those that did not state effect size, e.g. *blue shark 6/8* means *"Eight sets of results for blue sharks were extracted from the literature, six indicated that altering the depth of fishing gear had a significant effect on this species' catch rate"*. Points represent average fishing effort of control and treatment hooks combined, when reported. Dark bars = elasmobranchs, light bars = target species.

Additional floats, lines, clips and lead weights required to set surface longline gear deeper incurred a one-off set up cost of 3000 USD, and deeper lines generated 3% less revenue overall than shallower ones (Beverly et al. 2009). Setting deeper also increased the length of time it took fishers to set, by 30 minutes, and to haul, by two hours.

Comparison against criteria: Altering fishing depth can strongly reduce benthic shark bycatch but probably has a lower and less consistent impact on pelagic sharks (BLL, 4/5; SLL, 2/5); shallower setting in the hake bottom longline fishery had a minimal effect on target species, but deeper setting could strongly reduce surface longline target catch rates (BLL, 3/5; SLL, 1/5); shallower setting could have a positive impact on operations by reducing gear fouling and damage in bottom longline fisheries, but deeper setting resulted in large increases in time spent setting and hauling on surface longline gear (BLL 5/5; SLL, 1/5); no known safety hazards associated with setting depth (5/5); application could be reliant on self-reporting (1/5); fishers probably already vary their setting depths as they consider appropriate during the normal course of fishing and altering depth of gear can be achieved with standard, existing gear (5/5).

Score: BLL, 23/30; SLL, 15/30.

3.2.2 Avoiding seamounts and islands

Two studies looked at the effect of the proximity of fishing effort to seamounts or islands on shark catch rates (Bromhead et al. 2012, Gilman et al. 2012). These results are not graphed because effect sizes were not available. Both studies found that catches of pelagic blue sharks were likely to be lower when setting near seamounts. In contrast, bigeye thresher (*Alopias superciliosus*) (Gilman et al. 2012) and pelagic thresher (Bromhead et al. 2012) catch rates were higher near seamounts. Bromhead et al. found that setting near seamounts had a significant, negative effect on oceanic whitetip catches, while Gilman found no effect on the same species.

Score: No score allocated due to insufficient information.

3.2.3 Bait, alternative

Alternative bait: artificial

Holdsworth & Saul (2011) commented that blue sharks rarely took the artificial lures that gamefishers used to target billfish and tuna, while mako often took these artificial baits. Erickson & Berkeley (2008) used a different type of artificial bait, manufactured from fish processing waste products embedded in a gum-based matrix. When trialled on bottom longline gear targeting halibut (*Hippoglossus stenolepis*) in Alaska, this bait possessed good hook retention and produced significant reductions in spiny dogfish and longnose skate (*Raja rhina*) bycatches. Halibut catches were not affected but cod catches declined significantly. One variant of the artificial bait resulted in a 99% reduction in spiny dogfish catches. A pilot study of blue sharks in the field using non fishing gear found no reduction in this species on artificial baits.

Comparison against criteria: Bycatch of key shark species was strongly decreased on waste-derived artificial bait, but evidence came from a single, non-peer reviewed study that was carried out 14 years ago with no apparent further follow up (3/5); target species not present in New Zealand were unaffected but interspecific variation in teleost response was high, indicating that target findings cannot be extrapolated to New Zealand target species (1/5); hook retention of artificial bait was good, it maintained consistency after defrosting, could be cut to size and continued to fish for longer than natural bait, so it may be possible to develop a formula that does not negatively impact fisheries operations (3/5); no known safety hazards (5/5); use can be monitored from port (5/5); although trialled on fishing gear, development has not moved beyond prototyping and appears to have been discontinued (1/5).

Score: 18/30, but extensive development would be required to assess effect on New Zealand species.

Alternative bait: stingray

Echwikhi et al. (2010) found that stingray (*Dasyatis pastinaca*) bait significantly and strongly reduced sandbar shark (*Carcharhinus plumbeus*) catches compared to mackerel bait. Spinner sharks (*Carcharhinus brevipinna*) were also caught less frequently on stingray bait.

Score: No score allocated as using one elasmobranch as bait in an attempt to reduce another elasmobranch species' catch rate could be counterproductive, unless increased utilisation of stingray was a goal in addition to decreased shark bycatch.

3.2.4 Bait, dyed

Yokota et al. (2009) dyed squid blue and found that bait colour had no significant impact on catch rates of turtle or any elasmobranch species. Non significant changes in elasmobranch catches on blue dyed bait compared to plain squid varied from a 9% reduction in shortfin mako catches through to a 29% increase in pelagic stingray catches. Blue dyed squid caught 4% more blue shark than plain squid.

Score: No score allocated as dyed bait may hold limited potential as a method of reducing shark bycatch in commercial fisheries.

3.2.5 Bait, squid

Six studies compared shark catch rates on squid bait to those on fish bait (typically mackerel, *Scomber* spp.), and results varied widely both within and between species (Figure 5). Bigeye thresher catches were strongly and consistently reduced on squid bait. Squid bait also caught on average 13% (± 16 SE) less blue shark bycatch than fish bait in the studies that reported an effect size on squid bait relative to mackerel (Yokota et al. 2009, Amorim et al. 2014, Coelho et al. 2012). In contrast, Watson et al. (2005) found that the catch rate of blue sharks on mackerel bait was 40% less than on squid. Two of the largest studies reported significant increases in blue shark catch on squid bait (Foster et al. 2012, Petersen et al. 2009b). These results of these two studies were not graphed as the effect size was not stated.

Shortfin mako catches on squid bait were on average 18% (± 11 SE) lower relative to fish bait when an effect size was stated, but when studies that did not include effect sizes were considered, the picture became unclear with a range of significant and non-significant increases and decreases in mako catches on squid bait. Foster et al. (2012) found that porbeagle shark catches were significantly lower on squid bait than fish bait, but this finding is not included in Figure 5 because no effect size for porbeagle sharks was available. Foster et al. also found that Atlantic bluefin tuna catches were significantly higher on squid bait than fish bait, but again this species was not included in Figure 5 because no effect size was available.

Oceanic whitetip sharks, longfin mako, myliobatid rays and crocodile sharks (*Pseudocarcharias kamoharai*) showed large average increases in catch rates on squid bait, but a high degree of variability was present between study results. Each of these species was reported on by the same pair of studies, with one study reporting very large increases in catches on squid bait (Coelho et al. 2012) and the other reporting either no change or a reduction in catches (Amorim et al. 2014). These contrasting studies were carried out by the same scientists and both drew results from hundreds of thousands of hooks set in by Portuguese swordfish surface longliners in similar geographical regions over similar time frames. Speculatively, the bait used could have differed in quality.

Pelagic stingray catches on squid bait relative to fish bait also showed wide variation. Tuna catches, for both bigeye and yellowfin, were consistently higher on squid bait than fish bait, as were swordfish catches. Mahi mahi catches varied but were not significantly affected by bait type in any study.

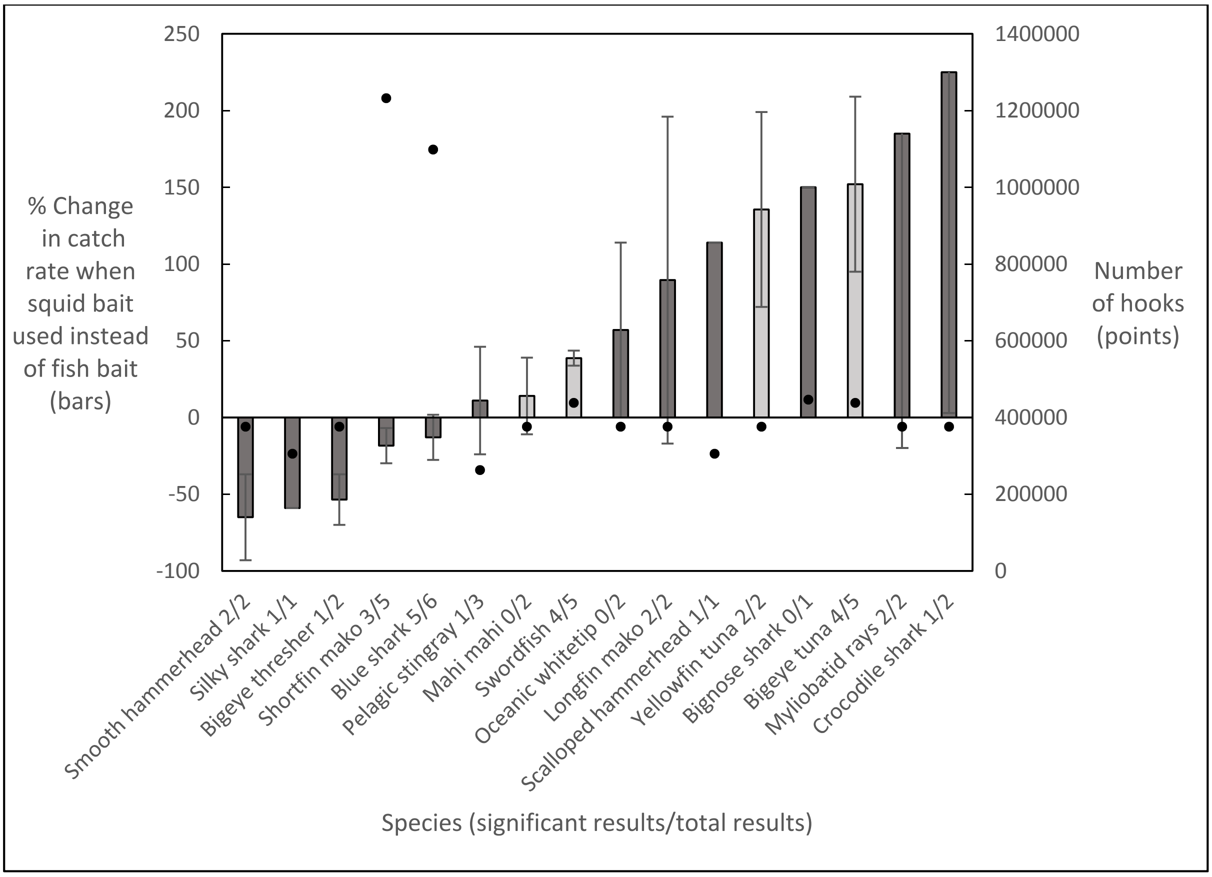

Figure 5: Average percentage change in elasmobranch and teleost catch rates when squid bait is used, compared to fish bait (typically mackerel), extracted from studies that stated effect size. Standard error bars shown. Only the negative standard error is shown for myliobatid ray and crocodile shark because the error bars were too large to display. Fractions following species names represent the number of significant results over the total number of results for that species, e.g. *blue shark 4/5* means *"five sets of results for blue sharks were extracted from the literature, four indicated that bait type (squid, fish) had a significant effect on this species' catch rate"*. Points represent average fishing effort of control and treatment hooks combined, when reported. Dark bars = elasmobranchs, light bars = target species.

Comparison against criteria: Bycatch of key New Zealand shark bycatch species (blue shark and shortfin mako) was on average moderately decreased on squid bait, but wide variation in effect was reported both within and between elasmobranch species (2/5); strong positive effect on target catches (5/5); no known effect on fishing operations (1/5); no known safety hazards (5/5); use can be monitored from port (5/5); widely used on commercial fishing gear (5/5).

Score: 23/30.

3.2.6 Baiting technique

Richards et al. (2012) compared the effect of hooking technique on mackerel bait to assess if more securely attached mackerel ("threaded") caught more sea turtles than single hooked mackerel. Tiger shark (*Galeocerdo cuvier*) catches on single hooked bait were 18% lower than those on threaded bait, and yellowfin tuna catches were also lower. Night shark (*Carcharhinus signatus*) catches were 35% higher on single threaded bait, and swordfish catches were also elevated. Only the reduction in yellowfin tuna catches was significant, but this study highlights the importance of bait attachment technique in study design. It was rare for any study in this review to describe how bait was attached to the hook.

Score: No score allocated as baiting technique may hold limited potential as a method of reducing shark bycatch in commercial fisheries.

3.2.7 Chemical deterrents

There is an historic, pre 1980 body of literature on chemical shark repellents that is reviewed by Hart & Collin (2015) but not addressed here, due to the age and rarity of many of their sources. Renewed interest in developing chemical shark deterrents followed the discovery that red sea soles (*Pardarchirus* spp.) excrete a surfactant substance that repulses sharks (Clark & George 1979), but most literature in this field focussed on synthesising this excretion rather than assessing its effectiveness as a shark deterrent. Zlotkin & Gruber (1984) demonstrated qualitatively that surfactants can cause sharks to cease feeding, while Sisneros & Nelson (2001) and Smith Jr (1991) demonstrated elasmobranch aversion to chemically treated baits.

The development of chemical shark deterrents has been continued by Stroud et al. (2014), but their semio-chemical deterrent made from decaying shark could be of limited use in a fisheries context for two reasons: the mode of delivery and the likelihood that effectiveness requires high local concentrations that may not be obtainable on bait exposed to an extended soak time (Abdul-Haqq & Shier 1991). At-sea trials of a semio-chemical treated squid were conducted in 2012 and earlier, but although these trials produced a reported 37% decrease in shark catch rates on surface longline gear (NOAA 2013), the methods and results of that study have yet to be peer reviewed.

Score: No score allocated as chemical deterrents in their current state of development may hold limited potential as a method of reducing shark bycatch in commercial fisheries.

3.2.8 Depth of fished water column

Four studies looked at how shark catches were affected by the depth of the water column where fishing activity occurred, independent of the actual depth where gear was set. These results are not graphed because effect sizes were not available. All three results for blue sharks indicated that blue shark catches increased significantly with ocean depth (Ferreira et al. 2011, Petersen et al. 2009b, Simpfendorfer et al. 2002). Likewise, oceanic whitetip, pelagic thresher and silky shark catches also increased significantly with ocean depth (Bromhead et al. 2012), as did swordfish catches (Ferreira et al. 2011).

In the absence of more information on both shark and target species, and finer scale data, targeting specific water column depths may not be a practical method of reducing shark bycatch.

Score: No score allocated due to insufficient information.

3.2.9 Electrosensory deterrents

Elasmobranchs possess a specialised electrosensory system that detects very weak electricity. Six field studies investigated elasmobranch catches on electrosensory deterrents, while a further 11 investigated the effect of electrosensory deterrents on elasmobranch feeding either in the laboratory or without using fishing gear. Materials used as electrosensory deterrents were electropositive metals, magnets and the Shark Shield, which emits a strong DC electric field.

Twenty three results were included for electrosensory deterrent catch rates on fishing gear in the field, and while all but one showed moderate to strong decreases in elasmobranch catches on electrosensory deterrents, only eight of these results were significant (Figure 6). Only field results on fishing gear are displayed in Figure 6 because many of the non-fishing gear studies report the presence or absence of a significant effect of electrosensory deterrents, but not an effect size. Amongst the 20 different results reported in non-fishing gear studies, 75% showed a decrease in elasmobranch feeding behaviours on electrosensory deterrents, and 45% showed a significant decrease. The average effect size, across the 13 non-fishing gear results where effect size was reported, was a 66% (± 11 SE) reduction in feeding behaviours.

Most electrosensory deterrent studies assumed that electropositive metal (EPM) and magnets would not affect teleost target species that lack the specialised electrosensory system common to all elasmobranchs. However, Godin et al. (2013) found a very large reduction in swordfish catches on EPM hooks. An even larger reduction in swordfish catches on procedural control hooks suggested that reduced swordfish catches on EPM lines were the result of the metal ingot acting as a visual deterrent. While tuna catch rates on hooks bearing electrosensory deterrents have not been assessed, there is evidence that yellowfin tuna are able to detect magnetic fields (Walker 1984), which could potentially enable them to detect electric stimulus via secondary magnetic fields.

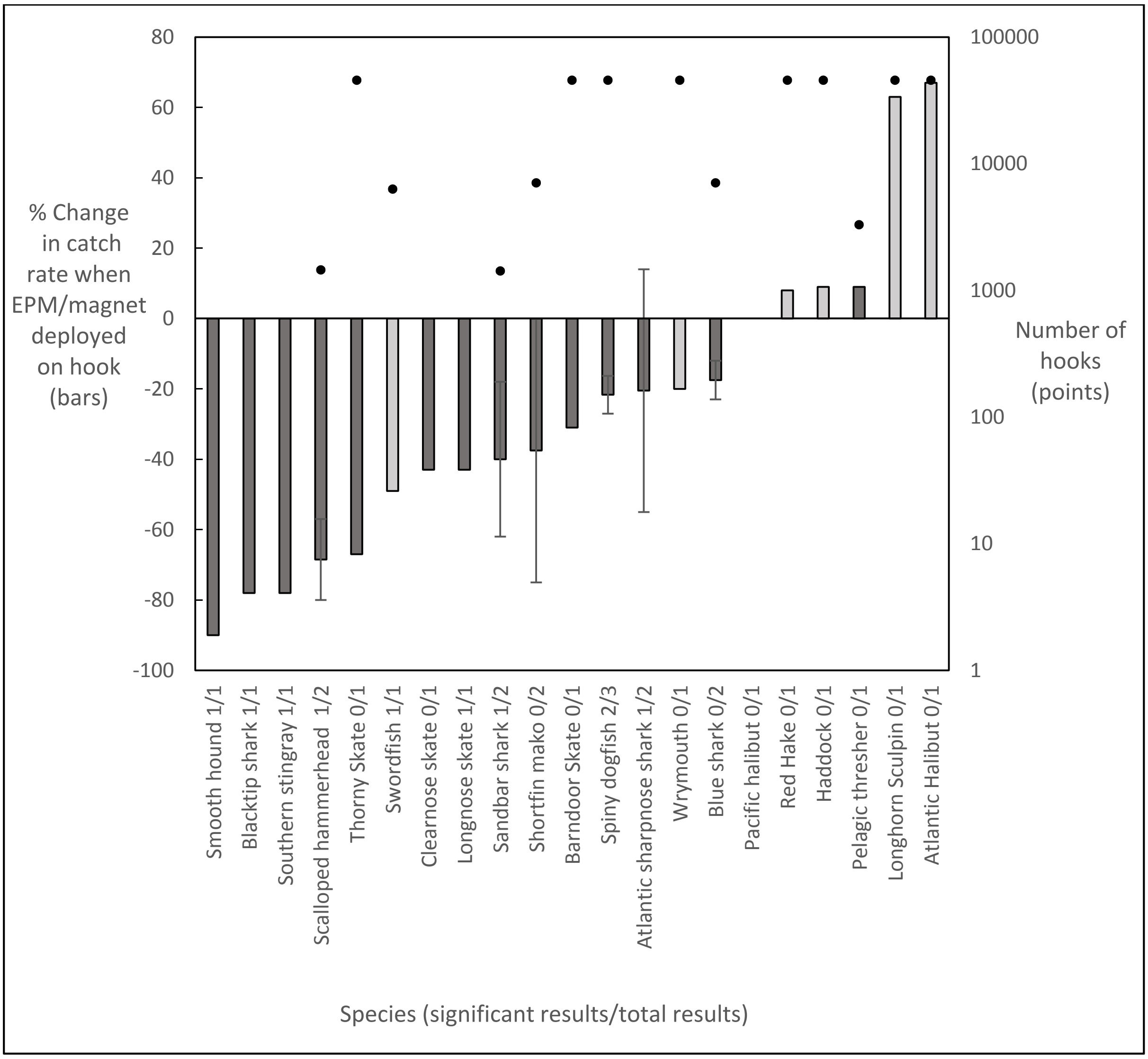

Figure 6: Average percentage change in elasmobranch and teleost catch rates on hooks associated with an electrosensory deterrent compared to control hooks, extracted from studies that stated effect size. Standard error bars shown. Fractions following species names represent the number of significant results over the total number of results for that species, e.g. *blue shark 0/5* means *"two sets of results for blue sharks were extracted from the literature, neither indicated that the electrosensory deterrent had a significant effect on this species' catch rate"*. Points represent average fishing effort of control and treatment hooks combined, when reported. Dark bars = elasmobranchs, light bars = target species.

Comparison against criteria: It is likely that electrosensory deterrents could reduce elasmobranch catch rates, but they may be less successful on pelagic species than benthic or coastal species (3/5); target species lacking an electrosensory system are unlikely to be affected by the electric stimulus produced by these materials, however more information is required to assess the impact on tuna, and the linked visual stimulus that might strongly reduce swordfish catches (1/5); electropositive metals would impact normal fishing operations because they corrode rapidly and require regular replacement, magnets could cause hooks to stick together (2/5); the precipitate caused by EPM corrosion poses a serious safety risk because it is highly flammable when dry (2/5); use can be monitored from port (5/5); development is currently at the stage of trialling prototypes on commercial gear but limited success has been attained with pelagic elasmobranchs (2/5).

Total score: 15/30.

3.2.10 Fewer lightsticks

Three studies looked at the effect of lightsticks on catch rates. These results are not graphed because effect sizes were not available.

Bigelow et al. (1999) found that increasing the number of lightsticks deployed strongly increased blue shark catches and slightly increased swordfish catches. Walsh & Kleiber (2001) also found that blue shark catches were lower on sets without lightsticks and increased with lightstick use. The effect of lightsticks on elasmobranch catches is probably species-specific, apparent in Piovano et al.'s 2010 finding that lightsticks had no effect on pelagic stingray catch rates.

Lightstick use accounted for less than 1% of the variance in blue shark and swordfish CPUE modelled by Bigelow et al. (1999), so while this study and Walsh & Kleiber (2001) found that lightsticks had a statistically significant effect on blue shark catch rates, it is likely that the practical significance of eliminating lightsticks is not great.

Comparison against criteria: Eliminating lightsticks could reduce blue shark catches but most variation in blue shark catches is probably not influenced by lightstick use, so the impact of this measure is probably low (2/5); the impact of using fewer lightsticks is unknown for tuna but could potentially reduce swordfish catches (1/5); using fewer lightsticks would be unlikely to affect normal fishing operations (4/5); no known safety hazards (5/5); application could be reliant on self-reporting (1/5); no development required (5/5).

Total score: 18/30.

3.2.11 Fishing at new moon

Seven studies looked at how elasmobranch catch rates varied with the lunar cycle. These results are not graphed because effect sizes were not available.

Blue sharks were the most frequently assessed species. Three out of the seven results for blue sharks indicated that catch rates were significantly higher during the full moon period (Damalas & Megalofonou 2010, Bromhead et al. 2012) or lower during the new moon (Vandeperre et al. 2014). This finding was not consistent, as both Poisson et al. (2010) and Ferreira et al. (2011) found that blue shark catches were higher on dark nights, and Petersen et al. (2009b) found that blue shark catches were significantly higher outside of the full moon period. It is possible that there is little practical significance of the impact of the lunar cycle on blue shark catches – Bigelow et al. (1999) found that despite the statistically significant relationship, lunar cycle explained less than 1% of the variance in blue shark CPUE.

Bromhead et al. (2012) also assessed bigeye and pelagic thresher CPUE and found that catches peaked around the full moon. Shortfin mako catches were not affected by the lunar phase (Petersen et al. 2009b).

Two studies presented a significant but contrasting influence of lunar cycle on swordfish catches: Bigelow et al. (1999) found that the CPUE of this target species peaked during the full moon, while Poisson et al. (2010) found that swordfish catches were lowest during the full moon.

Comparison against criteria: While lunar phase has been linked to reduced shark catches in some instances, it is likely that the relationship between elasmobranch CPUE and lunar cycle is highly complex and variable, both within and between species (2/5); there was insufficient information to assess the influence of lunar cycle on target species' CPUE (1/5); some New Zealand surface longliners target tuna over the full moon period, presumably due to greater fishing efficiency, so a shift to fishing at a different time of month could represent a profound change in fishing practices (1/5); no known safety hazards (5/5); application could be monitored from port (5/5); as an intervention outside of modelling-based studies, "fishing during the new moon" has yet to be trialled in a commercial or experimental setting and development would call for research investigating how this change could affect target catches, which might not be justified given the lack of evidence that this approach could reliably reduce shark catch rates (1/5).

Total score: 15/30.

3.2.12 Fishing by day

Four studies looked at how elasmobranch catch rates varied with the time of day that gear was soaked. These results are not graphed because effect sizes were available for only two species.

Bigeye thresher, blue shark, oceanic whitetip, shortfin mako and silky shark all showed at least one result for a significantly lower catch when fishing occurred during the day instead of at night (Bromhead et al. 2012, Gilman et al. 2012, Petersen et al. 2009b). Bigeye and yellowfin tuna catch rates were also significantly lower during the day (Gilman et al. 2012). Swordfish and mahi mahi catches were significantly higher during daylight hours, as were pelagic stingray catches (Gilman et al. 2012, Bromhead et al. 2012). Whoriskey et al. (2011) found that pelagic stingray and mahi mahi catches increased significantly during daytime fishing, by 186% and 94% respectively.

Comparison against criteria: Fishing by day instead of at night could potentially reduce bycatch of several pelagic shark species, but the size of this measure's effect is unclear (2/5); fishing by day could elevate swordfish and mahi mahi catches, while bigeye and yellowfin tuna catch rates would probably be negatively affected by a shift to daytime fishing (2/5); fishing by day would be unlikely to affect normal vessel operations (4/5); no known safety hazards (5/5); application could be reliant on self-reporting (1/5); development would rely on gaining a greater understanding of effects on target species, and resolving the issue of seabird bycatch that night setting can minimise (3/5).

Total score: 17/30.

3.2.13 Hook, appendage

Both Swimmer et al. (2011) and Sumpton et al. (2011) used an appendage to change the dimensions of the fished hook. Swimmer et al. used a short length of wire protruding on an angle from the posterior of a 14/0 circle hook to increase the hook's length and width, while Sumpton et al. used a short length of plastic that protruded laterally and anteriorly on a 14/0 circle hook. Sumpton et al. reported a 29% reduction in tiger shark catches and a 75% reduction in bull shark (*Carcharhinus leucas*) catches on these hooks, although the significance of these findings was not stated. Swimmer et al. reported reduced catches on appendage hooks for mahi mahi as well as a number of elasmobranchs including silky sharks and pelagic stingrays (Figure 7). Although not within literature search criteria, a New Zealand study on the effect of wire hook appendages on snapper (*Pagrus auratus*) catches found that target catch of legal sized snapper declined by as much as 17% on appendage hooks.

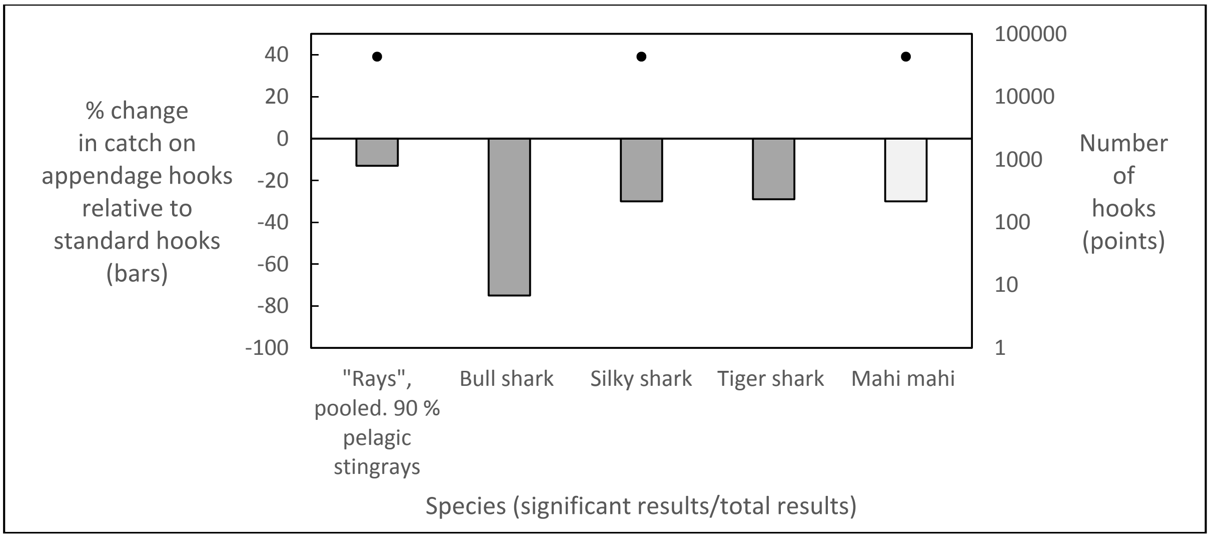

Figure 7: Reported percentage change in catch rate of elasmobranchs and teleosts on appendage 14/0 circle hooks relative to that on standard 14/0 circle hooks. Standard error not shown because each bar represents a single result. The effect of hook appendage on catch rate was significant for silky sharks only, all other species' results are either non-significant or untested. Points represent average fishing effort of control and treatment hooks combined, when reported. Dark bars = elasmobranchs, light bars = target species.

Comparison against criteria: Silky shark bycatch was moderately decreased by hook appendages, other elasmobranch species strongly decreased but supporting evidence is weak (2/5); likely to reduce target catches but supporting evidence for impact on pelagic targets is weak (1/5); effect on fishing operations unknown but wire appendages could be fragile or tangle prone (2/5); no known safety hazards (5/5); use can be monitored from port (5/5); prototypes trialled on commercial fishing gear (2/5).

Total score: 17/30. More information is required before the value of hook appendages as a method of reducing shark catches can be determined with any confidence.

3.2.14 Hook, circle

The effect of circle hooks as an alternative to J-hooks was systematically reviewed in the present study, but it is worth noting that recent and comprehensive reviews that address the role of circle hooks on shark bycatch already exist. Godin et al. (2012) conducted a meta-analysis into shark catch rates on circle hooks, extracting effect sizes like the present review, but unlike the present review, also weighted effect size against study power. Godin found that circle hooks did not influence shark catches significantly. Serafy et al. (2012) followed a symposium on circle hooks with a narrative review, and concluded that results were mixed and it is possible that circle hooks increased shark bycatch overall.

The present review included 19 studies that assessed the impact of circle hooks on elasmobranch catch rates, relative to either J-hooks or tuna hooks (See Figure 1 for an illustration of these different hook types). These studies looked at 21 elasmobranch species, and for all but three species, at least one result indicated an increased catch rate on circle hooks relative to tuna or J-hooks. Species that did not show any increases at all on circle hooks were bigeye threshers (reduction in catch rate on circle hooks ranged from 4 to 28%), salmon sharks (*Lamna ditropis*) (Yokota et al. 2006 found a 17% decrease in catches on circle hooks), and scalloped hammerheads (*Sphyrna lewini*) (an 8–62% decrease in catches on circle hooks). In addition, pelagic stingrays showed an average decrease in catch rates on circle hooks (Figure 8). The other species that showed an average decrease was the longfin mako, yet this average was drawn from two disparate results – a 66% decrease and a 48% increase in longfin mako catches on 17/0 circle hooks relative to 9/0 J-hooks (Amorim et al. 2014, Coelho et al. 2012). The average change in blue shark catches on circle hooks was an increase of 19% (± 4.4 SE). Where increases in shark bycatch occur on circle hooks, this is probably due to increased retention on the line rather than a true increase in shark catch rates. Circle hooks are more likely to lodge in the animal's mouth, whereas J-hooks are more likely to lodge in the gut (Watson et al. 2005). A nylon line running from the gut across the teeth is more likely to be bitten off than one attached at the mouth, addressed in the following section.

Hannan et al. (2013) found that circle hooks significantly increased catch rates of Atlantic sharpnose (*Rhizoprionodon terraenovae*) and blacknose sharks (*Carcharhinus acronotus*) on bottom longline gear, and individuals of both species caught on circle hooks were on average 5 cm shorter in fork length than those caught on J-hooks. They suggest that this size difference is because they used 15/0 circle hooks with a hook gape width that was 11 mm smaller than that of their Mustad #3 sized J-hooks. Reduced size selectivity of the smaller circle hooks could have biased the shark catch rate on circle hooks in this study.

All tuna species showed a strong average increase in catches on circle hooks, while mahi mahi results ranged from a 46% decrease through to a 56% increase in catches on circle hooks. Swordfish results showed a decline in catches on circle hooks, except for a single result that showed a 98% increase in swordfish catches on circle hooks (Andraka et al. 2013). Watson et al. (2005) found significant effects of hook type on hooking location in swordfish, and concluded that lower swordfish catches on circle hooks was due to a shift from gut hooking on J-hooks to mouth hooking on circle hooks, which was less likely to retain soft-jawed swordfish.

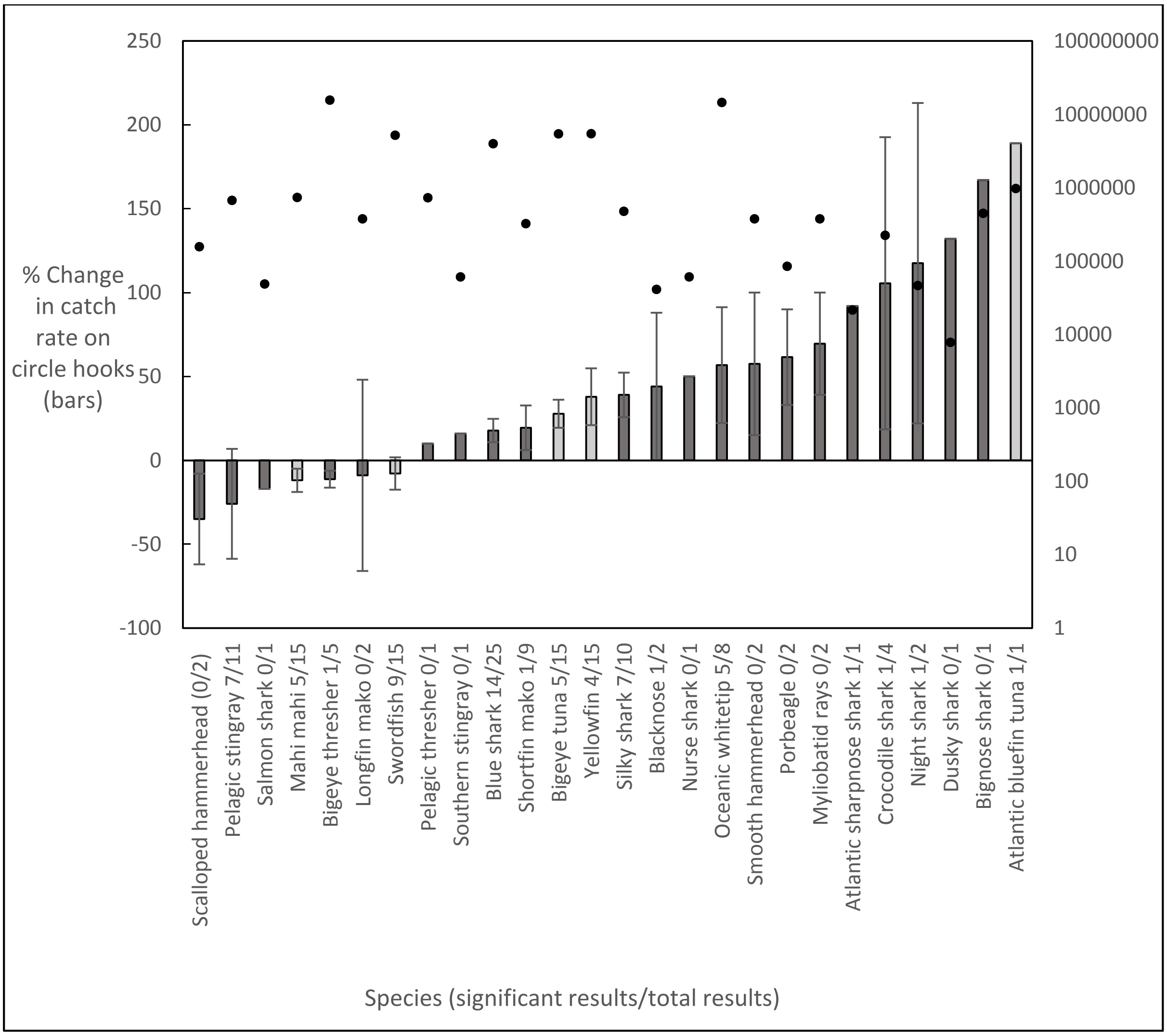

Figure 8: Average percentage change in elasmobranch and teleost catch rates on circle hooks relative to J-hooks or tuna hooks, extracted from studies that stated effect size. Standard error bars shown. Fractions following species names represent the number of significant results over the total number of results for that species, e.g. ***blue shark 14/25*** **means** ***"25 sets of results for blue sharks were extracted from the literature, 14 indicated that hook type had a significant effect on this species' catch rate".*** **Points represent average fishing effort of control and treatment hooks combined, when reported ("Number of hooks" values on vertical axis to the right). Dark bars = elasmobranchs, light bars = target species.**

Curran & Bigelow (2011) modelled the economic effect of circle hooks and concluded that the fleet wide mean annual gross ex-vessel losses if the Hawaiian surface longline fishery converted to circle hooks would be 8.1%. Losses came from reduced yellowfin tuna and mahi mahi catches, among others, although their randomisation test did not find a significant effect of circle hooks on tuna species. In contrast, Ward et al. (2009) estimated the value of actual catches in Queensland tuna surface longline fishery and found that the circle hook sets' total value was 13% higher than that of tuna hook sets. Finally, Amorim et al. (2014) found no effect of hook type on catch value per unit of fishing effort in a Southern Atlantic swordfish targeting fishery.

Within studies, the presence or degree of hook offset was often not controlled, and no attempt was made here to systematically review the effect of offset amongst the wide range of hook sizes, types and degrees offset used in included studies. Richards et al. (2012) found no significant effect of hook offset on elasmobranch or target species catch rates on pelagic surface longline gear. Hook offset might have little effect on catch rates or retention, but may influence where a fish is hooked. Watson et al. (2005) found that all circle hooks were significantly less likely to gut hook blue sharks and swordfish than J-hooks, but offset circle hooks were significantly *more* likely to gut hook than non-offset circle hooks.

Comparison against criteria: Circle hooks probably mitigate shark bycatch by improving the survival of caught sharks, but increase shark retention overall, so they were not scored as a candidate bycatch reduction method.

Total score: No score allocated.

3.2.15 Hook, double and guard

Sumpton et al. (2011) trialled several different measures of reducing non-shark bycatch on Queensland shark control drumlines, and reported the different measures' effects on shark catch rates as well as dolphins and other species. This low-powered study found that paired circle hooks presented back to back as a single "double hook" had no effect on shark catch rates, while hooks with a mesh "guard" draped over them caught significantly more sharks than those without the guard.

Score: No score allocated as double hooks and hook guards in their current state of development may hold limited potential as a method of reducing shark bycatch in commercial fisheries.

3.2.16 Hook, large

Piovano et al. (2010) found that size 2 J-hooks caught significantly less pelagic stingray than size 4 and 5 J-hooks, reducing CPUE of this species by 44% (Figure 9). The gape width of the size 2 J-hooks was 2.6 cm, while the smaller hooks had a 2 cm average gape width. For comparison, the 16/0 circle hook commonly used in New Zealand longline fisheries has a gape width of 2.7 cm. Similarly, Curran & Beverly (2012) caught 37% less pelagic stingray on 16/0 circle hooks relative to 14/0 circle hooks, although this difference was not statistically significant. Curran & Beverly (2012) also found non-significant decreases in blue shark catch rates on 16/0 circle hooks compared to smaller 15/0 and 14/0 circle hooks.

When Walker et al. (2005) assessed the effect of a range of different hook sizes on shark catch rates in a historic dataset they found a significant effect of hook size on catches of Port Jackson sharks (*Heterodontus portusjacksoni*) but not on the other 10 elasmobranch species that they caught in large enough volumes to meet the inclusion criteria for this review, and concluded that hook size had only a weak effect on benthic shark catches.

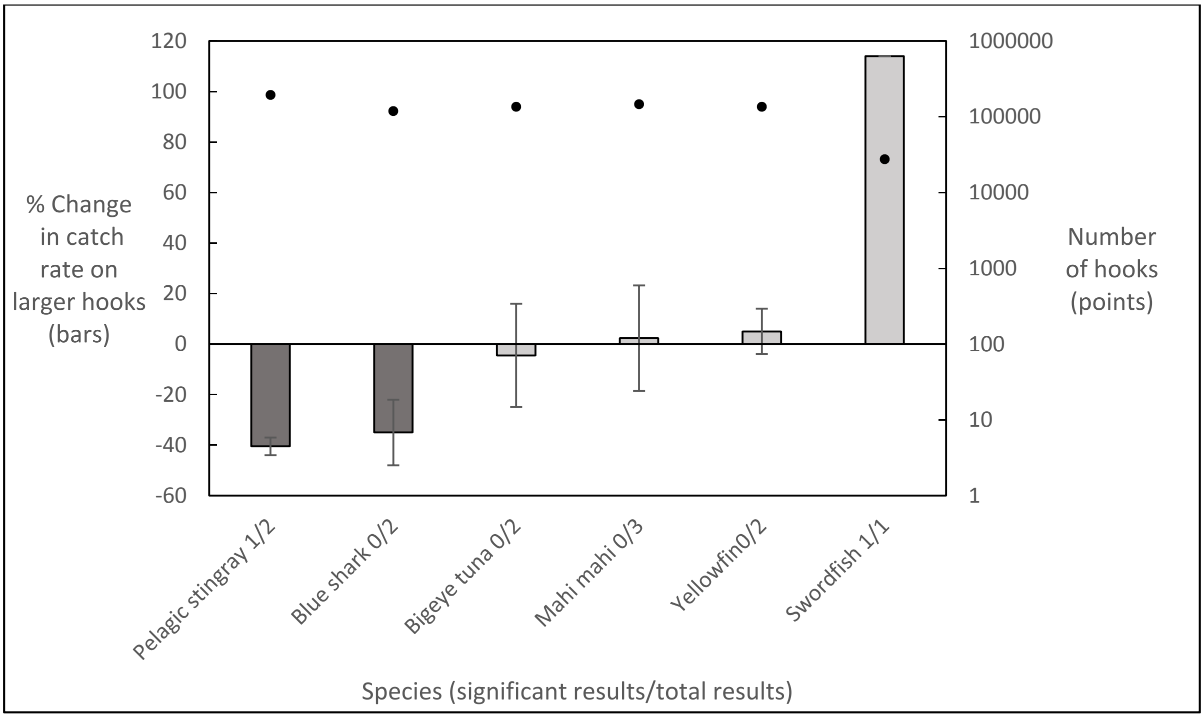

Figure 9: Average percentage change in elasmobranch and teleost catch rates on larger hooks relative to smaller hooks, extracted from studies that stated effect size. Standard error bars shown. Fractions following species names represent the number of significant results over the total number of results for that species, e.g. *blue shark 0/2* means *"2 sets of results for blue sharks were extracted from the literature, neither indicated that hook size had a significant effect on this species' catch rate"*. Points represent average fishing effort of control and treatment hooks combined. Dark bars = elasmobranchs, light bars = target species.

Comparison against criteria: Elasmobranch bycatch may be strongly decreased by using larger hooks, but effect could be species specific (4/5); the effect of hook size on target catches is likely to vary widely depending on target and size of hook (1/5); no known impact on fishing operations (5/5); no known safety hazards (5/5); use can be monitored from port (5/5); 16/0 circle hooks are commercially available and used widely (5/5).

Total score: 25/30 ***if*** bycatch species of concern is pelagic stingrays, but effect on catch rates of other elasmobranchs is not clear.

3.2.17 Hook, weak

There is limited peer reviewed information available on weak hooks, but their application to New Zealand fisheries targeting large bluefin or bigeye tuna could be inappropriate, given that they were introduced to USA surface longline fisheries in the Gulf of Mexico as a measure to reduce catches of large tuna (Foster & Bergmann 2012).

Weak 15/0 circle hooks that straightened under about 50 kg less pull force than standard 15/0 circle hooks were trialled by Bigelow et al. (2012). Not all of the straightened hooks released their catch and bigeye thresher were caught on straightened treatment hooks, illustrating that this species was capable of straightening them. Blue shark catch rates declined very slightly on weak hooks, and shortfin mako, pelagic stingray and oceanic whitetip catches were 10–50% lower on weak hooks than standard hooks.

The only significant effect in Bigelow et al.'s study was an increase in yellowfin tuna catches. Given that the treatment and control hooks were identical except for a 0.5 mm change in wire diameter, this finding could suggest that this study was underpowered despite the 302 000 hooks set. An alternative interpretation offered by a US longline skipper is that yellowfin catches are positively affected by weak hooks because the hooks are lighter than standard hooks (NOAA 2011).

Comparison against criteria: Bycatch could decrease but effect currently unknown, as is post-escape survival (1/5); effect on target catches is unclear – yellowfin catches could possibly increase, while opportunities to catch large individuals of any species could be lost (2/5); fishing operation could be negatively affected if their hook replacement rates increased (3/5); no known safety hazards (5/5); use can be monitored from port (5/5); commercially available but not used widely in commercial fisheries (4/5).

Total score: 20/30. More information is necessary before the value of weak hooks as a method of reducing shark catches can be determined with any confidence.

3.2.18 Nylon leader

Four studies of surface longline gear on commercial vessels targeting bigeye or swordfish addressed the effects of nylon leaders on shark catch rates and all found significant reductions in shark catches and significant increases in target catches (Ward et al. 2008, Vega & Licandeo 2009, Afonso et al. 2012, Caneco et al. 2014). Bigeye tuna and swordfish catches tended to increase, and while Caneco et al. (2014) reported a non-significant 2% decrease in yellowfin tuna catches on nylon leaders, overall yellowfin tuna catches appeared to increase on nylon leaders (Figure 10). Fishing effort across the studies ranged from 17 000 hooks to 75 000 hooks, and fishing locations ranged from the South Pacific Ocean to the South Atlantic Ocean. The average decrease in blue shark catches on nylon leaders, across the varying locations and levels of effort, was just over 30%.

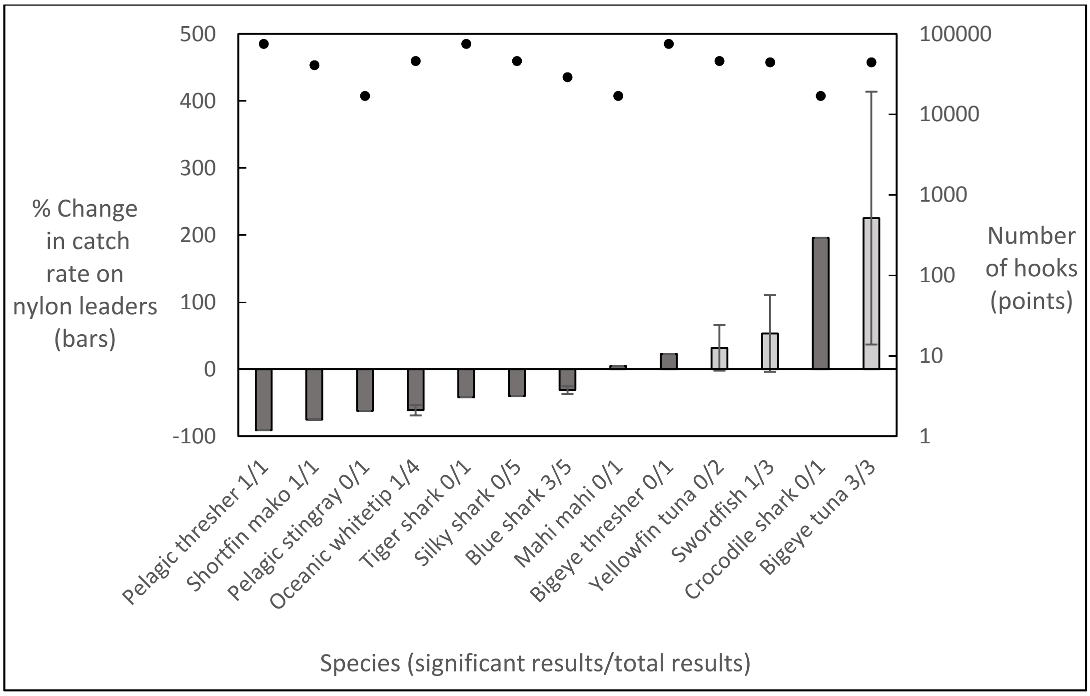

Figure 10: Average percentage change in elasmobranch and teleost catch rates on nylon leaders relative to steel leaders, extracted from studies that stated effect size. Standard error bars shown. The large standard error for bigeye tuna is due to one study reporting a 36% increase in catches and another reporting a 600% increase (Ward et al. 2008, Vega & Licandeo 2009). Fractions following species names represent the number of significant results over the total number of results for that species, e.g. *blue shark 3/5* means *"5 sets of results for blue sharks were extracted from the literature, 3 indicated that leader material had a significant effect on this species' catch rate"*. Points represent average fishing effort of control and treatment hooks combined. Dark bars = elasmobranchs, light bars = target species.

The apparent reduction in shark catches on nylon leaders is most likely due to increased bite off rather than a genuine reduction in shark catches. Afonso et al. (2012) found that a significant difference in shark catches due to leader type disappeared when hook bite off events were classed as undetected sharks. Ward et al. (2008) found that the rate of bite off increased with the local abundance of sharks, which supports the assumption that parted nylon lines represented undetected shark catches.

Ward et al. (2008) raised safety concerns about the hazard that parting nylon leaders bearing lead weights could pose to crew. Another operational consideration they identified is that nylon leaders had a 10% greater repair rate than wire leaders, but when they balanced repair costs against nylon leaders' increased target catch rates, nylon leaders had an annual net economic benefit of $8000 USD over wire.

Comparison against criteria: Bycatch of key shark species including blue shark, shortfin mako and pelagic thresher shark strongly decreased on nylon leaders (4/5); tuna target catch strongly increased (5/5); nylon leader could have some negative impact on operations due to increased maintenance requirements (3/5); there is a safety hazard due to leader parting that might be minimised through the development of "safe leads" (3/5); use can be monitored from port (5/5); nylon leaders are commercially available and used widely (5/5).

Total score: 25/30.

3.2.19 Shorter soak time

Seven studies assessed how longline soak time influenced shark catch rates. However, all but two of the studies defined "soak time" as including the haul. Larger catches can take longer to haul, so including the haul in "soak time" risks presenting an artificial positive relationship between catch rate and soak duration (Carruthers et al. 2011). Carruthers et al. (2011) used the variable "minimum soak time", defined as the period between the end of setting and the start of hauling, while Ward et al. (2004) estimated soak times per segment of line between buoys. Due to methodological differences between the studies, soak time findings were compared qualitatively.

Five studies assessed the effect of soak duration on blue shark catches. Carruthers et al. (2011) produced varied and inconclusive findings, while Caneco et al. (2014), Foster et al. (2012), Ferreira et al. (2011) and Ward et al. (2004) all reported blue shark catches that increased with soak time. Shortfin mako results from Foster et al. (2012) were significant but variable, while porbeagle catches decreased with soak duration, possibly indicating that dead animals were being lost over time. Caneco et al. (2014) also found significant positive relationships between silky shark catches and soak time.

The influence of soak time on some target catches varied between studies. Ward et al. (2004) found that catches of yellowfin tuna, bigeye tuna and swordfish tended to increase with soak time across all five fisheries assessed, and that in the southern bluefin fishery this species' catch rate also increased with soak time. Vega & Licandeo (2009) found that swordfish catches increased with soak time up to a 20 hour threshold, while gear set for longer caught fewer swordfish, presumably due to fish being lost. Ferreira et al. (2011) found that within the range of soak times in their study, which was approximately 20 hours or less, there was no significant effect of soak time on swordfish.

The timing of capture could give more insight than "total soak time" into the optimal soak duration that minimises shark catch rates. Poisson et al. (2010) found that the time when most sharks were caught overlaps with the time when most swordfish were caught. 60–80% of swordfish were caught in the first 4–6 hours after gear was set, and 60% of sharks were caught within the first 7 hours after gear was set. Like swordfish and sharks, the rate of bigeye tuna capture events also declined with increasing soak time. At the other end of the spectrum, mahi mahi captures tended to occur after 8 hours of soaking gear, and pelagic stingrays were more likely to be caught during the haul.

Despite having a relatively high at-haul survival rate overall, 70% of blue sharks died by the time 8 hours had elapsed after capture (Poisson et al. 2010). In this study, the maximum length of time that a blue shark survived after capture was 14 hours. Campana et al. (2009) looked at mortality rather than catch rates relative to soak time and, like Poisson et al., found that soak time significantly affected blue shark mortality rates. Mortality is not the focus of this review, but it is relevant to note that other operational variables can interact with soak time to influence shark mortality. For example, Carruthers et al. (2009) found that porbeagle and blue shark mortality increased with soak time on J-hooks but not on circle hooks.

In terms of implementation, Carruthers et al. (2011) pointed out safety and practical concerns that limit options for reducing soak time. Crew rest and eat while gear soaks, so any maximum soak time would have to account for their needs, while factors such as catch volume, gear damage and weather can have an unpredictable influence on soak and hauling time.

Comparison against criteria: Hook timer data suggests that sharks are caught early in the soak, so shorter soak time might not affect catch rates but could offer opportunities to improve survival. Although pelagic stingray captures were more common at the end of the soak, this is probably related to gear becoming shallower during hauling rather than actual soak duration. Non-hook timer data suggests that reduced soak time could reduce both shark catch rates (2/5) and target catch rates (2/5). The potential safety hazards of reducing soak time could be minimised by working closely with fishers to incorporate their working requirements into any minimum soak periods (3/5) but it is still likely that any minimum soak time could have strong effect on fishers' normal operations (1/5). Monitoring would probably depend on the presence of an observer (3/5). While limiting soak time would not require any new technology, it would call for development in the form of research that clarifies the possible impacts on shark and target species, catch rates, as well as shark mortality (3/5).

Total score: 14/30.

3.2.20 Targeting warmer water

12 studies assessed the impact of sea surface temperature on elasmobranch catch rates. These results are not graphed because effect sizes were rarely stated.

Blue sharks were the most frequently addressed species, accounting for 44% of the reported results. Blue shark catch rates were often significantly higher when sea surface temperatures were cooler (Bigelow et al. 1999, Caneco et al. 2014, Damalas & Megalofonou 2010, Ferreira et al. 2011, Foster et al. 2012, Vandeperre et al. 2014, Walsh & Kleiber 2001, Watson et al. 2005). Foster et al. (2012) modelled a 4–9% decrease in blue shark catches with each 0.6 °C increase in SST, within a SST range of 11–24 °C, while Bigelow et al. (1999) documented a peak in blue shark catches at 16 °C, within a range of 10–25 °C.

However, target species such as bluefin tuna might have stronger associations with cool water than blue sharks. While no results for Southern bluefin were available, Atlantic bluefin tuna catches were more affected by increasing water temperature than blue shark catches were, declining by 14–20% with each 0.6 °C increase in SST (Foster et al. 2012). Fishing warmer water to avoid blue sharks could be more achievable in fisheries targeting bigeye tuna, as catch rates of this species increased by 11–18 kg per 1000 hooks for every 0.6 °C increase in SST, within a SST range of 11–23 °C (Watson et al. 2005). Swordfish is a valued bycatch in the NZ surface longline fishery that targets bigeye tuna, and like blue sharks, swordfish catches could decline with increasing water temperature (Bigelow et al. 1999, Vega & Licandeo 2009).

Despite evidence that blue shark catch rates tend to be higher in cooler water, it is unlikely that this is due to physiological restrictions. Water temperatures where blue sharks are caught probably vary with sex and life history, as well as ecological factors. Carruthers et al. (2011) found that a relationship between SST and blue shark catches was only significant in one of the two seasons of fishing that they analysed, and speculated that the wide variability in blue shark catches over small spatial and temporal scales in their study could reflect blue sharks' responses to short term environmental changes other than water temperature. Damalas & Megalofonou (2010) found that the likelihood of encountering blue sharks declined linearly as water temperatures increased from 16 °C to 28 °C, but large concentrations of blue sharks were more common in warmer water. The influence of life history characteristics on blue sharks' presence in different water temperatures is also evident in Simpfendorfer et al.'s (2002) finding that male blue shark catch rates in the Northwest Atlantic were high between 15–20 °C, while female catch rates peaked at only 15 °C. Blue sharks' lack of a physiological restriction to cooler water was also demonstrated by Bromhead et al. (2012), who used data from fishing gear set in sea surface temperatures ranging from 27.5 to 30 °C, and found that blue shark catches peaked at 28 °C.

Other species of shark whose catches declined significantly with increasing water temperatures were bigeye thresher and pelagic thresher (Bromhead et al. 2012) as well as shortfin mako and porbeagle shark (Foster et al. 2012), while oceanic whitetip catches had a significant but complex relationship with water temperature (Bromhead et al. 2012).

Comparison against criteria: Despite CPUE for blue sharks typically peaking in lower sea surface temperatures, life history and ecological factors probably influence their distribution more strongly than SST (2/5); directing fishing effort to warmer water could strongly reduce bluefin tuna catch rates, moderately reduce swordfish catches and increase bigeye tuna catches (2/5); directing fishing effort to warmer water could strongly affect normal fishing operations by determining when and where fishing can occur (1/5); no known safety hazards (5/5); application could be reliant on self-reporting (1/5); fishers probably already vary their targeted water temperatures as they consider appropriate during the normal course of fishing. An appropriate method of defining "low shark encounter" water temperatures could rely on a comprehensive and regularly updated dataset defining the ecological and life history traits that influence distribution of relevant shark and target species in a local context, which would require extensive development and maintanence (1/5).

Total score: 12/30.

3.3 Ranking candidate shark bycatch reduction methods

After each bycatch mitigation method had been assessed for its potential as a tool in New Zealand longline fisheries, and allocated a score out of 30, candidates were ranked from highest to lowest scoring (Table 2).

Table 2: Rankings of candidate bycatch mitigation methods, based on scores against criteria in Table 1.

Candidate bycatch reduction method		**Score**	**Caveats**
1	Large hooks	25	
2	Nylon leader	25	
3	Squid bait	23	
4	Setting, shallower (BLL)	23	
5	Weak hooks	20	Limited information
6	Fewer lightsticks	18	Effect size small
7	Alternative bait, artificial	18	Limited information
8	Hook, appendage	17	Limited information
9	Fishing by day	17	
10	Fishing at new moon	15	
11	Electrosensory	15	
12	Setting, deeper (SLL)	15	
13	Shorter soak time	14	
14	Targeting warmer water	12	Focused on blue shark
15	Avoiding seamounts and islands	Limited potential	
16	Alternative bait, stingray	Limited potential	
17	Baiting technique	Limited potential	
18	Chemical	Limited potential	
19	Depth of fished water column	Limited potential	
20	Double hooks	Limited potential	
21	Dyed bait	Limited potential	
22	Hook, circle	Increases shark retention	
23	Hook guards	Limited potential	

4. DISCUSSION

4.1 Gear technology and bait

The main finding to emerge from this review is that most shark bycatch reduction methods that ranked highly in this study are already part of standard gear configurations in New Zealand longline fisheries. New Zealand tuna surface longline fishers typically use squid bait, large 16/0 circle hooks and nylon leaders at present, and nylon leaders are also common in bottom longline fisheries.

Although fish bait has been promoted over squid bait as best practice in shark bycatch mitigation (Gilman 2011), this review suggests that the case for fish bait as a shark bycatch reduction method is not strong. For two key New Zealand shark bycatch species, shortfin mako and blue shark, there is a tendency for catches to be lower on squid bait (Figure 5), while those elasmobranchs that showed increased catches on squid bait were caught at highly variable rates between studies (Amorim et al. 2014, Coelho et al. 2012). Given that target catch rates tend to be much higher on squid bait than fish bait (Amorim et al. 2014, Foster et al. 2012, Coelho et al. 2012), while evidence for fish bait as a means of reducing shark catches is inconsistent, there not a strong case for a shift to fish bait as a measure to reduce shark catches.

Compared to steel, nylon leaders increase the ability of a caught shark to bite free and escape from gear (Ward et al. 2008), and they are already mandatory in Australia and South Africa for this reason (Gilman et al. 2007a). However, unless the reduced shark retention rate on nylon leaders is accompanied by post-release survival, nylon leaders could mask shark bycatch mortality rather than mitigate it. Circle hooks *increase* shark retention on nylon leaders (Watson et al. 2005), but retained circle hooked sharks are more likely to be alive for release at the time of hauling than retained J-hooked sharks (Afonso et al. 2012, Afonso et al. 2011, Carruthers et al. 2009, Pacheco et al. 2011). Compared to J-hooks, circle hooked fish are also more likely to survive the period following escape or release than those caught on J-hooks (Horodysky & Graves 2005). This is because circle hooks typically catch a fish by the mouth, while J-hooks are more likely to lodge in the gut (Epperly et al. 2012). This explains the difference in shark retention on circle hooks compared to J-hooks – a gut hooked shark can more easily bite free from a nylon leader because the line runs out of the gut and across the teeth, while a mouth hooked shark might not have access to the leader with its teeth. The premise that circle hooks do not catch sharks at a higher rate than J-hooks, but rather reduce sharks' ability to bite off a nylon leader, is supported by Afonso et al. (2012). They found that wire leaders caught significantly more sharks than nylon leaders only when J-hooks were used. When circle hooks were used, shark catch rates no longer varied with leader type.

Another high scoring candidate bycatch reduction methods was the use of large hooks to increase gear selectivity. Piovano et al. (2010) found that a 16/0 circle hook took the least pelagic stingray catch out of all the hooks they trialled, so New Zealand surface longline fisheries are already applying best practice in selecting against this species. Sharks have a large mouth gape, but there is some weaker evidence to suggest that the 16/0 hooks can also reduce blue shark catch rates compared to smaller hooks (Curran & Beverly 2012). A 16/0 circle is mid-range in terms of the hook size used in international pelagic fisheries. For example, Afonso et al. (2012), Amorim et al. (2014), Coelho et al. (2012) and Pacheco et al. (2011) all documented successfully targeting bigeye tuna using 17/0 and 18/0 circle hooks, while hooks as small as 14/0 are also used in similar fisheries (Ward et al. 2009, Swimmer et al. 2010). Although these studies did not set out to assess the effect of hook size on shark catch rates, the persistence of sharks in their catches suggests that 17 and 18/0 circle hooks do not offer a panacea for shark bycatch. Even so, hooks larger than 16/0 could have a positive impact on elasmobranch bycatches, especially for rays. Assessing that impact would be best done with steel leaders, to minimise any risk of bias due to bite-off.

A limited set of target species catch rates were assessed in this review alongside shark catch rates, as effects on target species are likely to influence fisher uptake of shark bycatch reduction measures. Target species catch rates are also relevant because the efficiency with which target species are captured can indirectly affect shark bycatch. If target species catch rates declined due to a gear or operational change, fishers could compensate by increasing their fishing effort. If the decrease in shark bycatch was less than the decrease in target catches, compensating through increased fishing effort could negate the impact of a shark bycatch reduction method, even if the shark "bycatch per unit effort" was lower. Extrapolating from just one example for argument's sake, circle hooks have a strong, positive effect on pelagic target species' catch rates. Sales et al. (2010) found an average of 0.63 bigeye tuna and 24 blue sharks were caught per thousand circle hooks set by surface longliners near Brazil, and 0.32 bigeye tuna and 20 blue sharks were caught per thousand J-hooks. If J-hooks were implemented as a shark bycatch reduction measure, and fishers increased their fishing effort by 20% in an attempt to compensate for the amount that the J-hooks reduced their tuna catch, the outcome could be lower tuna catches paired with an unchanged total take of blue sharks.

E.g. 10 000 circle hooks = 6.3 tuna, 240 blue sharks.

10 000 J-hooks = 3.2 tuna, 200 blue sharks.

20% increase in J-hook effort: 12 000 J-hooks = 3.8 tuna, 240 blue sharks.

Hook appendages have been investigated as a method of reducing shark bycatch (Figure 7), and they probably function by increasing the hook's proportions so that it is harder for small-gaped fish to take the hook (Swimmer et al. 2011). If the mechanism of effect is the same, larger hooks could be a simpler method of achieving a similar result because unlike prototype appendage hooks, they are already commercially available. Larger hooks also have the advantage of lacking the protruding appendage that could get tangled in other fishing gear.

Weak hooks are another hook-based approach to reducing shark bycatch that scored highly. Like nylon leaders, they function by reducing retention rather than the absolute catch rate, and shark survival rates after escape is unknown. Despite having the potential benefit of preferentially releasing large sharks (Bigelow et al. 2012), which could favour the release of reproductive females, weak hooks might not be feasible in New Zealand tuna surface longline fisheries. Weak hooks are currently mandatory in United States Gulf of Mexico longline fisheries as a measure to reduce Atlantic bluefin tuna bycatch (Foster & Bergmann 2012), and an approach developed to *reduce* catches of large tuna is unlikely to be well received by the New Zealand tuna surface longline fleet. In New Zealand fisheries targeting fish that weigh less than 90 kg, weak hooks could be a good option for reducing retention of larger sharks.

Although not represented in the reviewed literature, one other alternative hook type is corrodible hooks, which can dissolve over time and are cheaper than standard hooks (WCPFC 2014b). Corrodible hooks could complement nylon leaders by enabling animals that escape from nylon leaders to spend less time with fishing gear attached to them. Corrodible hooks are mandatory in several United States-based pelagic longline fisheries, as a measure to facilitate sharks' hook loss (Anonymous 2002). The impact of corrodible hooks on long-term post release survival of sharks is unclear, as is the rate at which fishing operators would have to replace these hooks compared to stainless steel hooks.

Moving on from hook designs, artificial baits and electrosensory deterrents are two shark bycatch reduction methods that have potential to reduce elasmobranch catch rates but would require extensive development to realise that potential. While information about shark catches rates on artificial bait comes from a single study, the reductions in spiny dogfish and skate bycatches described by Erickson & Berkeley (2008) are very large, to the extent that spiny dogfish bycatch was almost eliminated on one bait type. An artificial bait manufactured from fish waste products could have the additional advantages of increasing utilisation of existing catches and reducing use of purpose-caught bait fish as well as reducing bycatch. It could also generate an economic benefit to fishing operators, if it was cheaper than the bait they currently use. However, Erickson et al. trialled multiple recipes for artificial bait before succeeding, and some of the baits trialled performed very poorly in catching target species (Erickson et al. 2000). It is likely that any attempt to develop a selective artificial bait in New Zealand would require working through many iterations of bait formula before determining if such an approach could successfully reduce shark catches without impacting target species catch rates.

In contrast to the very limited pool of literature available on artificial baits, electrosensory deterrents made up the third largest set of results in this review, after circle hooks and squid bait. As with artificial baits, despite the strong decreases in shark bycatch seen when electrosensory deterrents were deployed, their successful implementation in a fishery is neither guaranteed nor straightforward. Beyond their low success rate with pelagic sharks (Figure 6), the main obstacle to implementing them is the mode of delivering the electrosensory stimulus. To date this has involved using either a rapidly corroding, combustible ingot of electropositive metal, or a magnet with potential to stick to hooks. An alternative approach using zinc and magnesium was patented and trialled in association with the World Wide Fund for Nature in 2013, but appears to have been unsuccessful (Wimmer et al. 2014). The voltage gradient that these materials produce is well below the sensory threshold of non-electrosensitive target species (McCutcheon & Kajiura 2013), but as Godin et al. (2013) demonstrated, they can act as a visual deterrent to target species. Resolving these challenges would call for extensive research and development.

A final gear consideration with potential to reduce shark catches is the use of lightsticks, as blue shark catches tend to be lower on sets without lightsticks (Bigelow et al. 1999, Walsh & Kleiber 2001). Even so, the presence of lightsticks accounted for less than 1% of the variance in blue shark catches (Bigelow et al. 1999), and it is likely that eliminating lightsticks would not have very large effect on bycatch of this species.

4.2 Operational practices

Shallower setting of bottom longline gear was the highest ranked operational variable assessed. Where benthic elasmobranchs are the primary concern, this approach has strong potential to reduce bycatches (Figure 4). One example of a scenario where shallower setting might be beneficial is reducing skate bycatch in the ling (*Genypterus blacodes*) bottom longline fishery, as this group has been identified as showing the greatest decline amongst the bycatch species in this fishery (Anderson 2013). Coehlo et al. (2003) found that shallower setting had little impact on targeted hake catches, but ling consume more benthic prey than hake (*Merluccius australis*) in New Zealand (Dunn et al. 2010) so it is possible that ling catches could be more strongly affected by a move away from the benthos than hake catches.

Deeper setting of surface longline gear at night could potentially decrease blue shark catches while increasing bycatch of shortfin mako and pelagic stingrays (Bromhead et al. 2012, Swimmer et al. 2011, Beverly et al. 2009). The effect of altering setting depths on New Zealand surface longline target catches is unclear, but Beverly et al. (2009) reported decreased swordfish and yellowfin and improved bigeye tuna catches on deeper set gear. Here we can define "deeper" set surface longline hooks as those set more than 100 m in the water column.

Relative to the effects on bottom longline fisheries, shifting fishing depth in surface longline fisheries probably has a smaller potential impact on bycatches and the greater potential impact on target species (Figure 4). The biggest contrast between shifting fishing depth in surface versus bottom longline fisheries is probably practical – elevating gear from the benthos could benefit bottom longline operations by reducing fouling, but setting surface longline gear deeper could significantly extend setting and hauling duration in this fishery (Beverly et al. 2009).

Threshers and blue sharks make diurnal migrations to deep water during the day but are more likely to be in shallow water at night, and Bromhead et al. (2012) documented decreased blue shark catches when gear was set deeper at night. However, setting deeper to avoid a species found in the upper water column has the disadvantage of passing gear through the region where the bycatch species is commonly found. The second highest scoring operational method of reducing shark bycatch was fishing by day, which offers an alternative to altering gear depth in surface longline fisheries by setting gear at a time when blue sharks are more likely to be in deeper water. Like blue sharks, bigeye tuna also make diurnal migrations that take them to depths as great as 1000 m by day (Matsumoto et al. 2013). These dives are punctuated by brief but regular forays closer to the surface (Dagorn et al. 2000), so it might still be possible to target bigeye tuna with shallow set lines by day. This approach might have varying success in reducing blue shark catch rates, because blue shark vertical migration behaviour can vary widely both within and between individuals (Queiroz et al. 2012). If this approach to shark bycatch mitigation were of interest, the next step could be to further investigate the diurnal vertical migration patterns of relevant shark species. A shift to day setting would also require a solution to the seabird bycatch problem that day setting would exacerbate.

Clarke et al. (2014) suggest that the species-specific variation in depth and temperature ranges mean that a "shallow-deep approach to mitigating shark catches is overly simplistic". "Targeting warmer water" was the lowest scoring candidate bycatch reduction method, largely because the effect on the catch rates of elasmobranchs and target species was unclear. Targeting warmer water could significantly reduce blue shark, shortfin mako and porbeagle shark catches, but to a lesser extent than the expected reductions in Atlantic bluefin tuna catches in those same temperatures (Foster et al. 2012). If southern bluefin tuna responded similarly, this would pose a major obstacle to uptake of this method. Bigeye tuna-directed fisheries could be more amenable to this approach, because bigeye tuna are a tropically distributed species (Li et al. 2012, Patterson et al. 2008). Even so, water temperature is unlikely to be the most important factor in determining blue shark distribution. Ferreira et al. (2011) point out that behaviours such as feeding or reproduction probably influence blue sharks' distribution in the water column more than physiological limitations, because those physiological limitations are overcome during the large vertical migrations that this species makes. It is likely that differences in male and female blue sharks migration patterns could lead to sex, regional and seasonal differences in how blue shark catches vary with water temperature (Simpfendorfer et al. 2002).

Lunar phase was another environmental variable assessed, as "fishing during the new moon" could hold potential as a measure to reduce shark catches. While many of the reported results identified significant relationships between lunar phase and catch rates of different elasmobranch species, it appears that this relationship is highly complex and variable, both within and between species.

Although excluded from the quantitative review on the basis that their study did not measure shark catch rates, the "*TurtleWatch*" tool developed by Howell et al. (2008) offers an example of how information generated by this "environmental modelling as a predictor of bycatch" approach has been applied in a fisheries bycatch reduction initiative. *TurtleWatch* was intended to provide the Hawaiian surface longline fleet with maps of real-time sea surface temperatures and ocean currents alongside predicted locations where sea turtle interactions are more likely. Following *TurtleWatch's* roll out, fishing effort actually intensified in areas identified as high risk for sea turtle bycatch. Even so, the *TurtleWatch* programme is still active today in Hawaii.

Along similar lines, researchers at the University of Delaware have recently announced their intention to develop a "daily bycatch forecast" that will use environmental data and fish tracking data to predict the location of shark bycatch hotspots (Messmore 2014). This initiative is in the early stages of development and draws on large, pre-existing environmental and biological datasets for the Delaware region.

The influence on shark catch rates of environmental variables such as those modelled for the "daily bycatch forecast" are likely to vary through time and space, but results addressing seasonal variation, location and "distance from land" were all excluded from this review. The interaction between season, location and shark catch rate is likely to vary with elasmobranch species, ontogeny and sex, and possibly also population. Attempting to encompass such a vast and variable body of knowledge was beyond the scope of this review, but in-depth species-specific analysis of interactions between catch rate, life history, environmental, spatial and temporal variables in a New Zealand context could offer new approaches to minimising local shark bycatches.

Finally, shortening gear soak time was another low scoring candidate bycatch reduction method, due to potential impacts on target catch rates, uncertainty about this approach's merit in reducing shark catches, and the operational and safety impacts that this measure could have (Carruthers et al. 2011). The most important point to come out of literature on this topic is that if further research were to investigate the shark bycatch reduction potential of shortening the period that gear is soaked, the definition of "soak time" should exclude hauling to avoid confounding large catches' slower haul times with an effect of soak duration. Poisson et al. (2010) demonstrated the value that hook timers can bring to this line of investigation, by providing a clearer picture of when different species are caught, and how long they survived after capture.

5. MANAGEMENT IMPLICATIONS

The highest scoring methods of reducing shark bycatch were large hooks baited with squid on nylon leaders, which is consistent with current standard practice in the tuna surface longline fishery. This was an unexpected outcome, given the inclusion of fish bait over squid as part of accepted best practice in surface longline shark bycatch mitigation (Gilman 2011). The effect of squid bait was not investigated for any benthic elasmobranchs, so this could be an avenue for future research.

Despite the association of circle hooks with increased shark retention, their tendency to mouth hook rather than gut hook could make them a key component on gear that includes nylon leaders, which might otherwise mask shark mortality due to gut hooked animals biting off the leader. A shift to even larger circle hooks than the 16/0 hooks commonly used in New Zealand surface longline fisheries could potentially reduce elasmobranch catches even further, especially for pelagic stingrays or other species with similar mouth-morphology or feeding behaviour. If alternative larger circle hooks were investigated, steel leaders would give more accurate data on absolute shark catch rates, rather than the shark retention rates reflected on nylon leaders.

Another hook based approach that could be implemented rapidly is corrodible hooks, which would not mitigate shark bycatch but could potentially reduce the amount of time that escaped or cut off sharks spend trailing gear. More information regarding the impact of corrodible hooks on shark post release survival, as well as the hooks' lifespan compared to standard hooks would be necessary to assess their value as a shark bycatch mitigation method, and also their practical impact on fishing operations. There is a gap in the literature where this research has either not been carried out or not published.

A shift in setting depths could strongly reduce shark bycatches, but the effect on different shark species, target catches and vessel operations could be very different between bottom and surface longline fisheries. It is likely that extensive further research would be required to assess whether such a shift was justified and understand how time of day and lunar cycle could influence that effect of altering fishing depth. Even so, such a change could be much less development-intensive than implementing environmental predictors such as water temperature as a bycatch reduction tool, which researchers at the University of Delaware are currently attempting with "super computers (and) one of the most heavily instrumented (marine) areas in North America" (Messmore 2014). Incorporating data on New Zealand shark catch rates relative to gear depth or temperature would be the next step toward understanding the influence of these variables on local shark catch rates, as none of the studies included in this review were conducted in New Zealand waters. Bromhead et al. (2013) emphasised the difficulties of using models built from observer data to investigate factors influencing shark bycatch, and encouraged controlled experimental fishing trials as a means to "tease apart" the many interacting variables.

Finally, a novel approach identified as a promising avenue for further exploration is the development of artificial bait manufactured from fish processing waste. Artificial bait showed strong reductions in shark catch rates with limited impacts on target species, but would require extensive further development to reach a fisheries-ready stage, and evidence of success with pelagic shark species is limited.

6. ACKNOWLEDGMENTS

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APPENDIX 1. SEARCH TERMS

Table 3. Search terms and initial inclusion criteria used to identify relevant publications in systematic literature review. Searches were conducted in the SCOPUS academic literature database, as well as the Ministry for Primary Industries publication database. Google Scholar was also searched, non systematically.

Search	Database type	Search name	Search terms	Initial inclusion criteria	Relevant hits
1	Academic	Current practice in longline shark bycatch mitigation	(shark OR elasmobranch OR chondrich* OR dogfish OR turtle) AND (fisheries OR fishing OR longline OR "baited gear") AND (repel* OR deter* OR bycatch OR barrier OR reduc* OR mitigat* OR avoid* OR aversion OR "non target" OR interaction)	- Field study - Baited gear - Compares environmental or operational variables to shark catch rates *OR* - Behavioural study that aims to deter sharks from bait.	66
2	Academic	Longline shark surveys	(shark OR elasmobranch OR chondrich* OR dogfish) AND (survey OR "fishery independent")	- Field study - Baited gear - Compares environmental or operational variables to shark catch rates	18
3	Academic	Electrosensory bycatch reduction devices (BRDs)	(shark OR elasmobranch OR chondrich* OR dogfish) AND (magnet OR electr*) AND (repel* OR deter* OR bycatch OR barrier OR reduc*mitigat* OR avoid* OR aversion OR "non target" OR interaction)	- Elasmobranch behavioural or field study - Electric stimulus is a variable - Aim is to deter sharks	31
4	Academic	Vision-based BRDs	(shark OR elasmobranch OR chondrich* OR dogfish) AND (light OR light-dark OR vision OR visual) AND (repel* OR deter* OR avoid*)	- Elasmobranch behavioural or field study - Visual cue is a variable - Aim is to deter sharks or reduce bycatch	1
5	Academic	Chemical BRDs	(shark OR elasmobranch OR chondrich* OR dogfish) AND (chem* OR semio* OR surfactant OR olfact*) AND (repel* OR deter* OR avoid*)	- Elasmobranch behavioural or field study - Chemical cue is a variable - Aim is to deter sharks or reduce bycatch	17
6	Academic	Acoustic BRDs	(TITLE-ABS-KEY(shark OR elasmobranch OR chondrich* OR dogfish) AND TITLE-ABS-KEY(sound OR noise OR acoustic) AND TITLE-ABS-KEY(repel* OR deter* OR avoid*))	- Elasmobranch behavioural or field study - Acoustic cue is a variable - Aim is to deter sharks or reduce bycatch	1
7	Academic	Environmental and operational variables	(shark OR elasmobranch OR chondrich* OR dogfish) AND (longline OR "long line") AND (hook OR depth OR current OR oceanography OR environment* OR bait OR soak OR time OR operation* OR season OR temperature OR benthos OR "sea floor" OR habitat OR location OR area OR hotspot or "sea mount" OR aggregate*) AND (bycatch OR mitigate* OR "non target" OR interaction)	- Field study - Baited gear - Compares environmental or operational variables to shark catch rates	57
8	MPI publication database	Current practice in longline shark bycatch mitigation	Shark	- Field study - Baited gear - Compares environmental or operational variables to shark catch rates	5

Search	Database type	Search name	Search terms	Initial inclusion criteria	Relevant hits
				OR - Behavioural study that aims to deter sharks from bait.	
9	MPI publication database	Current practice in longline shark bycatch mitigation	Elasmobranch	- Field study - Baited gear - Compares environmental or operational variables to shark catch rates *OR* - Behavioural study that aims to deter sharks from bait.	1
10	MPI publication database	Current practice in longline shark bycatch mitigation	Ray	- Field study - Baited gear - Compares environmental or operational variables to shark catch rates *OR* - Behavioural study that aims to deter sharks from bait.	1
11	MPI publication database	Current practice in longline shark bycatch mitigation	Dogfish	- Field study - Baited gear - Compares environmental or operational variables to shark catch rates *OR* - Behavioural study that aims to deter sharks from bait.	0
12	MPI publication database	Current practice in longline shark bycatch mitigation	Bycatch	- Field study - Baited gear - Compares environmental or operational variables to shark catch rates *OR* - Behavioural study that aims to deter sharks from bait.	3
13	Academic	Hook appendages	"hook appendage" AND bycatch	- Field study - Baited fishing gear with hook appendages - Measures shark catch rates.	0
14	Academic	Circle hooks	"circle hook"	- Field study - Baited gear - Compares hook type to shark catch rates	48