Review of mitigation techniques for set net fisheries and applicability to New Zealand fisheries

BPM-DOC-New Zealand setnet mitigation review-1.0

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Prepared by: Simon Childerhouse, Elanor Miller and Verity Steptoe
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Table of Contents

List of Figures

List of Tables

Appendices

1. Executive Summary

Perhaps unsurprisingly, the conclusions from this review are similar to those of the previous Conservation Services Programme (CSP) reviews by Bull (2007b) and Rowe (2007), as well as the recent global review by Waugh *et al.* (2011). This consistency in conclusions primarily reflects a lack of new approaches or techniques being introduced into the field of bycatch mitigation and a stronger focus on refinement or additional testing of existing methods.

Globally, mitigation has focused on four main techniques: acoustic deterrents; spatial and temporal closures; gear modifications and operational modifications. Over half of the literature reviewed was related to acoustic deterrents, over a quarter spatial and temporal closures, and the remainder split between gear and operational modifications.

In general terms, studies of the techniques tended to provide inconsistent and sometimes conflicting results regarding mitigation of protected species bycatch. These results varied by the protected species, the location of the fishery, the way the fishery operates and the time of year. Almost all mitigation techniques involved a trade-off between a reduction in bycatch and impact on the fishery.

Of the techniques reviewed, spatial and temporal closures, and acoustic deterrents (i.e. pingers) have the most research potential for application to New Zealand set net fisheries. While pingers have shown to be highly effective in some fisheries overseas, studies indicate they are unlikely to be effective for coastal delphinids, including Hector’s and Maui’s dolphins and other protected species in New Zealand. In contrast, there is excellent evidence of the effectiveness of spatial and temporal closures in reducing bycatch levels for all protected species investigated, when applied at an appropriate scale. This technique should, therefore, be most effective in reducing the bycatch of protected species in set nets in New Zealand. In order for spatial and temporal closures to be effective, however, they must be driven by clear, management goals for both protected species and fisheries, and be thoroughly evaluated against them.

Based on an assessment of the mitigation techniques reviewed, we make the following recommendations for future research on the mitigation of protected species bycatch in New Zealand set net fisheries:

- The most effective form of protected species bycatch mitigation is spatial and temporal closures. In order to ensure that management decisions are based on robust and reliable data, research should focus on the development of quantitative models that can assess the likely impacts of closures on both bycatch rates and fisheries. Such models are likely to be data intensive if they are to be reliable and robust. They should also include consideration of the displacement of fishing effort from closed areas and the impact of this on overall bycatch levels;
- In order to assess the effectiveness of any mitigation technique it is essential that a target for bycatch reduction be developed. This could take the form of a Potential Biological Removal (as has been already applied to Hectors and Maui’s dolphins) or some other metric that is relevant to the protected species;
- For species that already have Potential Biological Removals, these should be reviewed in light of the scale of known or estimated set net mortality and assessments made of the potential costs and benefits of spatial or temporal closures;
- Any research into the mitigation of bycatch in set nets should include an assessment of effectiveness for both commercial and recreational set netting; and
- There has been little research on mitigating the bycatch of protected species other than dolphins and this is an area for future work, including potential work on shearwaters, penguins and shags.

In summary, there is no silver bullet for mitigation of protected species bycatch and no single method will work in all fisheries, for all areas, all species and at all times. Species- and fishery-specific solutions, therefore, need to be explored. In addition, the effectiveness of mitigation can only be determined when clear management goals are identified, quantified and articulated to all stakeholders, and when implemented mitigation is backed up by dedicated enforcement and compliance monitoring regimes.

2. Introduction

One of the most significant and global anthropogenic threats to marine wildlife is the incidental bycatch of non-target marine species through fishing activities (Read *et al.* 2006). New Zealand Fishery observer records show that even with the current mitigation techniques in place, protected species (e.g. cetaceans, pinnipeds, seabirds and other marine species) have been observed interacting with the commercial set net fishery resulting in entanglements, injuries and deaths. Odontocetes (i.e. tooth whales) are commonly caught, including dusky dolphins, Hector's dolphins and in one instance, a pilot whale, which was released alive (Rowe 2009, 2010a; Ramm 2010, 2011). Bycatch records show that New Zealand fur seals were bycaught every year between 2005 and 2010. Diving seabird species also appear to be at a high risk of set net entanglement, with various species of petrel, shag, shearwater, and yellow eyed penguins commonly caught (Rowe 2009, 2010b; Ramm 2010, 2011). Other protected marine species are caught occasionally, including the white shark, caught during both the 2008/09 and 2009/10 fishing seasons, as well as in earlier years (Ramm 2010, 2011; Francis & Lyon 2012), and the green turtle, fatally entangled during the 2008/09 season (Waugh *et al.* 2011). Fishers have also reported the capture of species that have not been identified by fishery observers, including a humpback whale, released alive in the 2008/09 season, as well as several unidentified toothed whales (Abraham & Thompson 2011). There have also been anecdotal reports of non-target species being incidentally taken through recreational set net fishing, but the extent and specific species involved are largely unknown due to lack of data from fishers and no regulatory action.

For protected species in particular, including those listed as threatened or critically endangered, any mortality in these populations can have severe conservation implications. The potential and observed bycatch of Maui's and Hector's dolphins in set nets is one of the ongoing primary marine conservation issues in New Zealand.

The efficacy of various mitigation techniques employed in set net fisheries has been investigated globally. The majority of effort has focussed on cetaceans but there have also been limited studies on pinnipeds, seabirds and other marine species. The techniques investigated include acoustic deterrents, spatial and temporal closures, and operational and gear modifications. Their success in reducing or eliminating the incidental catch of non-target species depends on many factors including the type of fishery and fishing vessels, the time of year, geographical location and the assemblages of potential bycatch species present in the area. A general conclusion from these studies is that before widespread application of a mitigation technique, it is important to understand the potential long-term impact on the behaviour and ecology of the bycaught species. It is also necessary to consider the impact on target species catch rates and the associated economic and social costs, as well as the complexity in managing fishery participation and compliance.

As is the case for fisheries elsewhere around the world, bycatch mitigation in the New Zealand set net fishing industry may require a compromise between maintaining populations of marine species at a desirable level, and economic and community benefits relating to both commercial and recreational fishing activities (Morzaria-Luna *et al.* 2012). However, in the instance of the Maui's dolphin (and to lesser degree, Hector's dolphin), there is little room for compromise, as the loss of an individual animal threatens the survival of the species. Effective measures focused on conservation rather than economic value are therefore required without delay, to ensure fishing practices do not further contribute to their decline and likely extinction.

Regulated and voluntary mitigation techniques currently in place in the New Zealand set net commercial and recreational fishing industry primarily involve spatial and temporal closures and changes to fishing activity (MPI 2013a). These stringent measures have been largely driven by the recognised threat to the critically endangered Maui's dolphin, nationally vulnerable Hector's dolphin and dusky dolphins. Other current measures include changes to fishery operations, such as limited soak times, compulsory observer presence on board, monitoring of active fishing gear and restrictions on net height (MPI 2013a). In addition, there has been an increasing presence of observers on board commercial set net fishing vessels in order to monitor bycatch and target species catch rates.

There have been previous reviews of research on mitigation techniques for the bycatch of marine species and how they could be applied in New Zealand's fisheries (Bull 2007b; Rowe 2007). This report covers bycatch mitigation studies for gill net fisheries that have occurred since the last reviews in 2007, and includes an assessment of new research, efficacy of mitigation techniques, and their relevance for application to New Zealand gill net fisheries (referred herein as 'set net' in order to acknowledge the term most commonly used by New Zealand fishers). Based on a review of this research, recommendations on mitigation techniques that may potentially be applied to New Zealand set net fisheries, and areas where further research is required are discussed.

3. Project Scope

The project aim is to:

- Identify and assess the current mitigation techniques for both marine mammal and seabird capture employed in set net fisheries both domestically and internationally, and make recommendations as to their applicability to the New Zealand situation.

The project scope is to:

- Conduct a review that will build on the previous DOC-funded reviews by Bull (2007b) and Rowe (2007), as well as the recent global review by Waugh *et al.* (2011);
- Review current and historic research; including, but not limited to, international scientific literature, government agency commissioned reports, conference proceedings, commercial research and industry trials;
- Identify mitigation methods and analyse each in terms of the scientific rigor of any reported trials, the level of proven efficacy in any reported trials, and their relevance to the New Zealand situation; and
- Describe in detail these methods and outline and compare costs and benefits of each mitigation technique, highlighting uncertainties and caveats of reported trials, and making recommendations for areas of future research.

The project outputs are:

- A written report detailing the mitigation techniques available to set net fisheries in New Zealand and assessment of the costs and benefits associated with these techniques highlighting uncertainties and caveats of reported trials, particularly in respect to the protected species assemblages likely to be effected in New Zealand; and
- A set of recommendations for areas of future research.

An issue raised in relation to this review is that switching gear types (e.g. from set nets to bottom lines) could be considered as a form of mitigation. Based on the terms of reference for this review, we took the strict interpretation that mitigation was defined as a technique that could reduce bycatch levels <u>for set net fisheries</u> and so have not considered gear switching during the review. We do, however, note that switching gear type does have the potential to reduce bycatch rates for protected species but that it was considered outside the scope of this review.

4. Methods

The methods for this review are fully described in a previous report to the Conservation Services Programme (CSP), with a presentation of the methods provided on the CSP website[1]. A summary of the methods is also provided here.

4.1 General approach

The literature review included the following sources: international scientific literature, government agency commissioned reports, conference proceedings, commercial research and results from industry and scientific trials. We also used the considerable body of grey literature on mitigation techniques for incidental bycatch in set net fisheries. Although difficult to source, this is a huge and valuable source of relevant information. We reviewed all literature through direct searching of conference, workshop, meeting and observer programme reports, which are often not well referenced in electronic databases. Electronic search engines and databases were used, including Web of Science, Current Contents, Google Scholar, and general internet searches. We used keywords such as: gillnet, set net, mitigation, bycatch. This review builds on the previous DOC-funded reviews by Bull (2007b) and Rowe (2007), as well as the recent global review by Waugh *et al.* (2011).

In addition to general literature searches, we used the following two databases, which considerably improved the primary research tools for this research. These were:

- The Bycatch Reduction Techniques Database
  Hosted by www.bycatch.org, the database is managed by The Consortium for Wildlife Bycatch Reduction. This group of researchers and fishers work together in order to solve issues of bycatch. The Consortium supports collaborative research between scientists and the fishing industry to identify practical bycatch reduction solutions for endangered species; and
- The Project GLoBAL website (Global Bycatch Assessment of Long-lived Species[2]). This (along with other useful information) contains an extensive bibliography and recent publications (i.e. over 1,500 catalogued references) from the Project GLoBAL team.

Both of these specialist and highly relevant databases were excellent sources of material for this review.

4.2 Review and analysis of mitigation literature

All of the sourced literature was reviewed against the following criteria, which are expanded from those identified in the CSP Annual Plan 2012/13:

1) Description of the fishing technique, including:
   - 1.1 Target fish species;
   - 1.2 Region of interaction;
   - 1.3 Gear configuration (e.g. demersal, mid water, pelagic);
   - 1.4 Relevance to the New Zealand set net fishery; and

[1] Available at http://www.doc.govt.nz/Documents/conservation/marine-and-coastal/marine-conservation-services/mit-2012-03-setnet-mitigation-review-presentation-7-3-12.pdf
[2] Available at http://bycatch.nicholas.duke.edu

1.5 Relevance to the protected species assemblages likely to be affected in New Zealand.

2) Description of the mitigation technique, including:

2.1 Level of scientific rigor of any reported trials;

2.2 Level of proven efficacy in any reported trials (i.e. in both reducing protected species bycatch but also in maintaining target fish catch);

2.3 Any caveats or uncertainties in the methods;

2.4 Relevance to the New Zealand set net fishery;

2.5 Relevance to the protected species assemblages likely to be affected in New Zealand; and

2.6 Costs and benefits.

3) Potential areas for making recommendations for areas of future research in New Zealand.

5. Results

5.1 Review of previous mitigation research

This review builds on previous DOC-funded reviews of this issue by Bull (2007b) and Rowe (2007), as well as the recent global review by Waugh *et al.* (2011). These previous reviews identified six main mitigation techniques that have been reported in the literature (Table 1). Overall, there was good agreement between the three reviews in their conclusions, which can be summarised briefly as:

- No single method will work in all fisheries, for all areas, all species and all times. Therefore species- and fishery-specific solutions need to be explored;
- Many mitigation techniques showed little evidence of mitigating bycatch, and where there was evidence, it often corresponded to a reduction in target catch rates as well;
- Seasonal and area closures are most effective at mitigating bycatch but exclude fishing and are therefore unlikely to be considered a feasible option in all fisheries;
- More research is needed including proper experimental trials; and
- Increased observer coverage is required in order to understand interactions.

Table 1: Summary of mitigation techniques described by previous reviews – Bull (2007b), Rowe (2007) and Waugh *et al.* (2011).

Mitigation Technique	**Bull (2007b)**	**Row (2007)**	**Waugh *et al.* (2011)**
	Sea birds	**Marine mammals**	**Various species**
Net modifications		*	*
Passive reflectors		*	*
Pingers	*	*	*
Sub-surface setting	*		*
Time of setting	*	*	*
Time/area closures	*	*	*

These three previous reviews were used to guide the work in this review and, as a result, we did not review the literature prior to 2007 but have referred to work referenced in the three reviews.

5.2 Summary of new literature reviewed

Throughout this literature review, 79 published and unpublished reports with relevance to set netting and mitigation techniques were identified. Most (68%) of these were published scientific reports, while unpublished and Government reports constituted 17% and 15% of the literature reviewed respectively (Figure 1). Most had direct relevance to mitigation but some of the reports described fisheries and interactions rather than providing information on specific mitigation techniques. These were considered potentially relevant in understanding and characterising interactions.

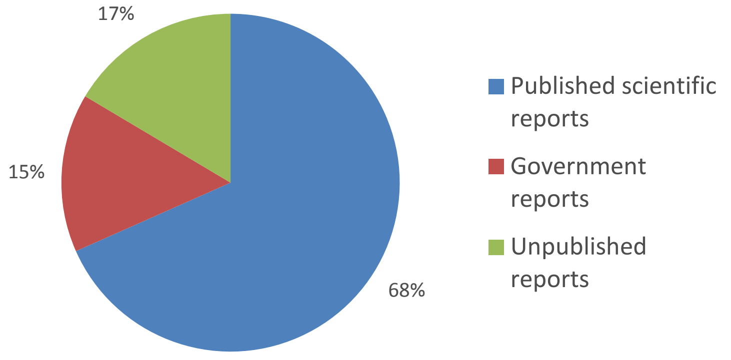

Figure 1: Type of literature reviewed (n=79).

As per the project scope, only documents from 2007 onwards were reviewed. It was assumed that the reviews of Bull (2007b), Rowe (2007) and Waugh et al. (2011) sufficiently assessed relevant information prior to this date. In terms of number of reports, there was a spread of literature across the period 2007 to 2013 (Figure 2). Of the literature reviewed, most reported on mitigation of cetacean bycatch (48%) or the mitigation of more than one species (24%) but a variety of species were covered (Figure 3). The focus for this review was New Zealand protected species but we broadened the scope of the review in order to include other related issues that we thought relevant to bycatch mitigation (e.g. electronic monitoring (EM) of set net operations).

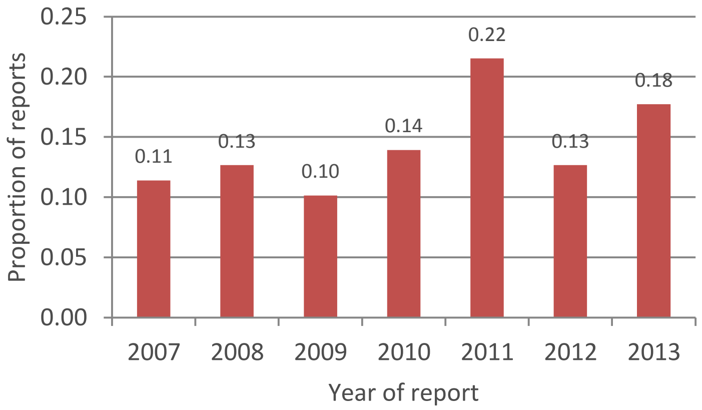

Figure 2: Year of literature reviewed (n=79).

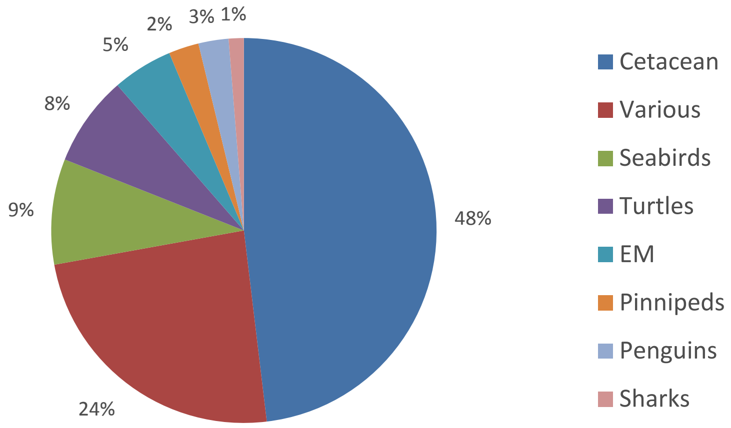

Figure 3: Subject taxa or group of literature reviewed (n=79).

5.3 Detailed analysis of mitigation literature

Of the 79 reports and papers reviewed, only 35 (44%) contained information specifically relevant to the development, testing and implementation of mitigation techniques. A summary of these specific papers, and the nature of the information contained within each is provided in Appendix 1. The remainder of the reports provided some information relevant to bycatch mitigation but were mainly focused on other issues such as providing a description of bycatch interactions in set net fisheries, a description of set net fisheries where bycatch occurs, or information about the magnitude of the interaction. While all of these references have been used to inform the final analysis, they contained insufficient relevant information to warrant the detailed assessment that was applied to the 35 key papers and reports listed in Appendix 1.

The 35 key papers and reports can be broken down by fishery gear type and target species (Figure 4, Figure 5). Following the previous three reviews, mitigation can be characterised as four main types: acoustic deterrents, spatial and/or temporal closures, gear modifications and operational modifications. A breakdown of the literature by these four main themes (Figure 6) showed that just over half (51%) of the literature was related to acoustic mitigation techniques, and the remainder split between spatial and/or temporal closures (26%), gear modification (14%) and operational modifications (9%).

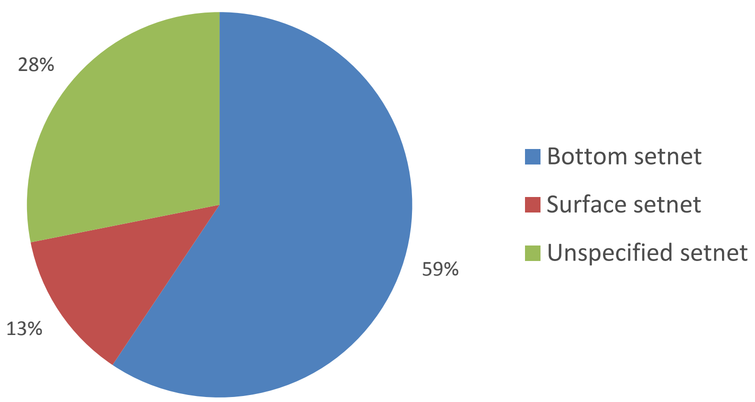

Figure 4: Fishery gear type of literature reviewed (n=35).

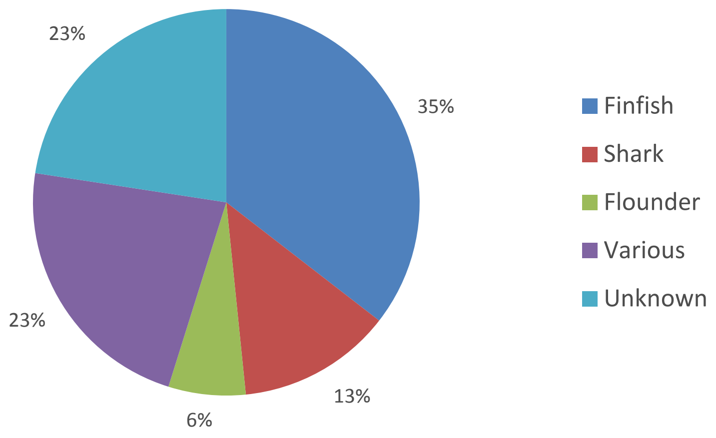

Figure 5: Target species of literature reviewed (n=35).

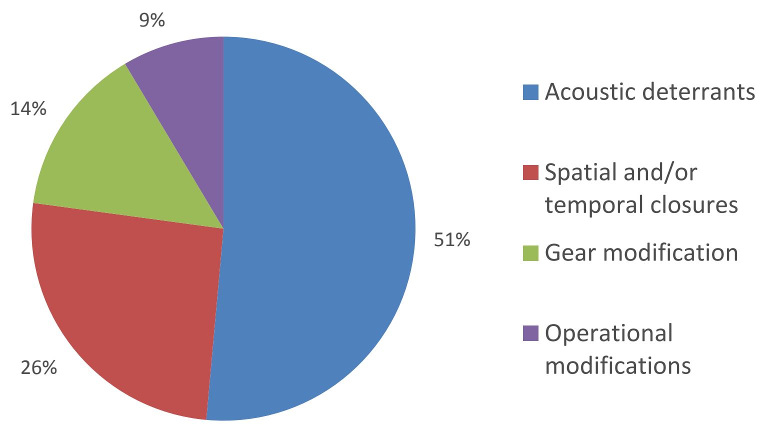

Figure 6: Mitigation type of literature reviewed (n=35).

5.4 Spatial and temporal closures

A detailed summary of each paper relevant to spatial and temporal closures is provided in Appendix 1. A brief overview and summary of some of the key papers is provided here with a general discussion in Section 6.

Spatial and temporal closures have been found to be an effective way to significantly reduce bycatch of protected species in set net fisheries (Goldsworthy *et al.* 2010; McClellan *et al.* 2009; Morzaria-Luna *et al.* 2012). Several studies sought to assess the potential effectiveness of closures in reducing bycatch and also in quantifying fisheries losses.

Morzaria-Luna *et al.* (2012) used ecosystem modelling in order to compare trade-offs between different spatial management scenarios for the conservation of the critically endangered vaquita porpoise *(Phocoena sinus)*. It was determined that a sustained increase in vaquita abundance would only occur with extensive spatial closures to fisheries, which are the primary source of income for many people.

McClellan *et al.* (2009) assessed the effectiveness of closures in Pamlico Sound, North Carolina in reducing sea turtle bycatch. Using predator-prey type models in order to assess spatial correlation in fishing effort and turtle habitat use, they were able to identify high-risk areas and determined that current closures, though controversial, were well placed to be effective. The primary recommended management scenario would result in large economic costs to the fisheries in question, particularly the set net fishery.

Goldsworthy *et al.* (2010) drew on data from satellite tracking, observer and fishing effort, to assess the extent and impact of bycatch across populations of the Australian sea lion *(Neophoca cinerea)* in South Australia. They found bycatch levels under current fishery closures to be unsustainable. Assessment of different management scenarios indicated that closures based upon female core foraging areas would provide the greatest reduction in bycatch rates (i.e. with up to 95% of female bycatch being reduced when the fishing area was reduced by 50% in identified foraging areas). Under these closures, fishing effort would need to be removed rather than displaced. Hamer *et al.* (2011, 2013) also found current closures to be insufficient, due to the regular movement of sea lions beyond the boundaries of protected areas. Extensions to current boundaries based upon animal tracking data and habitat use were recommended.

Similarly, Neimi *et al.* (2013) quantitatively assessed the distribution of Saimaa ringed seals (*Pusa hispida saimensis*) using GPS and VHF tags. They found that current seasonal closures covered 63% of the estimated seal distribution, while gear restrictions applied to only 55% of the area used by the seals. Due to the high risk of bycatch and threat of extinction, they recommend that protected areas be expanded to cover the entire range of this species.

In a review of closures aimed at protecting vaquita from set net bycatch, Rojas-Bracho & Reeves (2013) concluded that recent protection efforts have likely slowed the species' decline, but the goal of eliminating set nets by 2012 was not reached. Some reasons for this include the voluntary nature of mitigation techniques and opposition from the national fisheries agency. Enforcement of set net bans within the vaquita refuge area had also been lacking in recent years and as a result, illegal fishing (with inherent bycatch) has increased substantially.

Slooten (2013) reviewed the effectiveness of closure-based management in reducing Hector's and Maui's dolphin bycatch within New Zealand. The review determined that population recovery is unlikely under current protection measures. Without fisheries mortality, it is estimated that populations could almost double by 2050. Under current management however, the probability of recovery for the species as a whole is 20%, assuming set nets are removed completely from protected areas and effort is not displaced elsewhere. If 50% of the fishing effort previously inside the protected area is displaced, then this probability of recovery drops to 8%. In most areas, dolphin distribution extends well beyond the offshore boundary of the current fishing closures. The only closure to have indicated some level of effectiveness has been the Banks Peninsula Marine Mammal Sanctuary. Estimated bycatch rates have decreased here from 35-46 per year to 23, though there is still considerable overlap in fishing effort and dolphin distribution. In other areas there has been no evidence of a substantial bycatch reduction, and in the far north and south regions bycatch appears to have increased slightly. Lack of observer coverage in most areas has made it difficult to accurately quantify bycatch rates and determine closure effectiveness. Overall, Slooten (2013) recommended that protected areas be increased to cover all waters <100 m deep, including harbours, and that a protected area in Cook Strait be established in order to avoid further population fragmentation.

5.5 Acoustic deterrents

A detailed summary of each paper relevant to acoustic deterrents is provided in Appendix 1. A brief overview and summary of some of the key papers is provided here with a general discussion in Section 6.

Many studies over the last 20 years have investigated the efficacy of acoustic deterrents in reducing marine mammal bycatch. Pingers are the most commonly tested devices, and results have varied, depending on the bycatch species and area studied. There has been considerable variation in the success of pingers in reducing bycatch:

- The greatest success rate appears to be for beaked whales (Carretta *et al.* 2008) and harbour porpoise (*Phocoena phocoena*) (Alfaro Shigueto 2010; Gönener & Bilgin 2009; Northridge *et al.* 2011; Palka *et al.* 2008);
- There have been varying degrees of success for bottlenose (*Tursiops truncatus*), common (*Delphinus delphis*), striped (*Stenella coeruleoalba*) and franciscana dolphins (*Pontoporia blainvillei*) (reviewed by Dawson *et al.* 2013).
- There has been little or no evidence of success for Hector's (*Cephalorhychus hectori*) (Stone *et al.* 1997, 2000), Indo-pacific humpback *(Sousa chinensis)* (Berg Soto *et al.* 2009; Soto *et al.* 2012) and tucuxi dolphins (*Sotalia fluviatilis*) (Monteiro-Neto *et al.* 2004) although there have been only limited studies on these species.

As a result of previous research, pingers are currently mandatory in several commercial fisheries, including the Gulf of Maine groundfish gill net fishery and the California drift net fishery under various 'Take Reduction Plans' (NOAA 2013a, 2013b). The mandatory use of pingers in the California drift net fishery was concluded to be the primary reason for the recorded 100% decline in bycatch rates of beaked whales over the course of 17 years of observations, rather than other mitigation techniques applied during the same period, which included seasonal closures and limitations on fishing depth (Carretta *et al.* 2008).

Bycatch rates of harbour porpoise were found to be significantly reduced in several studies although the statistical power of these results vary. In a large dataset from the NE Atlantic, Palka *et al.* (2008) found pingers to result in significantly less bycatch, but only in the absence of pinger failure. For example, those nets with an incomplete set of pingers had greater bycatch than those with none, and it was suggested that porpoises may perceive a gap in functioning pingers as a gap in the net. Bycatch reduction for this species as a result of pingers has also been recently demonstrated in the Black Sea (Gönener & Bilgin 2009) and Peru (Alfaro Shigueto 2010). Two simulated studies of pinger effectiveness found a significant decrease in the echolocation rate of porpoises around active pingers (Berggren *et al.* 2009; Hardy *et al.* 2012). EU regulations require vessels >12 m in length to use pingers throughout static nets in order to minimise risk to cetaceans. While the use of pingers has proved effective for harbour porpoise, fishers are concerned with the impracticalities of using such a high number of devices (Northridge *et al.* 2011). Tests of louder devices, DDDs (Dolphin Dissuasive Devices), have suggested that they may be effective up to 10 times the distance as pingers, but bycatch reduction rates were not as high (e.g. ~65% compared to ~90%) (Northridge *et al.* 2011). Further testing is needed as sample sizes were too small to be statistically robust. Larsen *et al.* (2013) conducted a controlled experiment testing the effect of increased pinger spacing on Harbour porpoise bycatch in the Danish North Sea. Current regulations in this area require pingers to be spaced no more than 200 m apart, but this study found spacing at 455 m to result in 100% bycatch reduction compared to fishing without pingers.

Most studies examining bottlenose dolphins focused on depredation of prey from nets rather than bycatch rates. Depredation causes economic losses to the fishery through reduced catch and net damage, as well as conservation concerns, as animals often become entangled. Studies show varied responses by bottlenose dolphins to pingers, with some indications of a decrease in net damage and greater target species catch (Brotons *et al.* 2008b; Buscaino *et al.* 2009; Gazo *et al.* 2008) and decreased interaction rates (Waples *et al.* 2013). However, as Dawson *et al.* (2013) highlight, there have been two other studies where fatal entanglements of bottlenose dolphins have occurred in nets equipped with pingers (Northridge *et al.* 2003; Read & Waples 2010).

Common dolphin response to pingers has also been inconsistent as highlighted by Berrow *et al.* (2008). This simulated study on the South Coast of Ireland found no evidence of avoidance to active pingers, while Carretta and Barlow (2011) found a 50% reduction in common dolphin bycatch with pinger use in the Californian gill net fishery.

Pingers have been used sporadically in the New Zealand set net fishery (Ramm 2010, 2011), however low observer presence and lack of compliance prevented conclusions being made on their efficacy in reducing bycatch of protected marine species.

5.6 Gear and operational modifications

A detailed summary of each paper relevant to gear and operational modifications is provided in Appendix 1. A brief overview and summary of some of the key papers is provided here with a general discussion in Section 6

5.6.1 Acoustic detectability

Few studies investigated the effect of increased net acoustic detectability on reducing animal entanglement. Larsen *et al.* (2007) enhanced nets using iron oxide and concluded that while bycatch rate of harbour porpoise was reduced, results were confounded by concurrent differences in net stiffness. Catch of target cod was also reduced by approximately 30% and fish caught in modified nets were generally smaller. Similar modifications using barium sulphate were also unsuccessful in reducing bycatch of fransiscana in Argentina (Bordino *et al.* 2013; Mackay, 2011).

5.6.2 Visual deterrents

There have been very few studies on visual deterrents as a means to reduce bycatch of marine species. One recent study tested the efficacy of different visual modifications on reducing green turtle bycatch in set nets in Baja California, Mexico (Wang *et al.* 2010). The addition of shark shapes deployed during daylight hours, significantly reduced bycatch by 54%, but also resulted in a reduction in target species catch rate and value. Illumination of nets with chemical light sticks and LED lights were found to have negligible impacts on target catch, and reduced bycatch by 60% and 40% respectively.

5.6.3 Hanging ratio

Schnaittacher (2010) investigated whether the hanging ratio (i.e. the hanging ratio measures how tightly the net is stretched along the head and foot rope) of a set net has an impact on harbour porpoise bycatch in the Gulf of Maine. While the results presented were only preliminary, the only apparent effects were an increase in target species catch rate with a hanging ratio of 0.33 compared with 0.5. In a well-designed study in Pamlico Sound, North Carolina, Price and van Salisbury (2007) found that bycatch of turtles was significantly reduced in nets set with a lower profile, while target species catch was maintained. Mackay (2011) suggests that lower net profile may not show similar reductions for cetaceans.

5.6.4 Increasing tension

Thorpe and Frierson (2009) investigated the impact of increasing net tension on the bycatch rates of shark species. Tension was increased through the addition of larger floats and greater lead line weight and is assumed to reduce wrapping entanglement and increase manoeuvrability around and through the net. Results showed that the modified net significantly reduced the bycatch of Atlantic sharpnose shark and blacknose shark species but not the bycatch of blacktip or bonnethead sharks. Catch rate of target species was unaffected.

5.6.5 Tie downs

Tie downs have been found to reduce the incidence of harbour porpoise bycatch by lowering the net profile (Fox *et al.* 2011). Bycatch rates of short beaked common dolphins were also decreased, while target catch rate and size increased. Further data are needed in order to determine the significance of these results due to low sample size.

5.7 Other issues

In addition to the mitigation issues discussed above, we also reviewed relevant information about other relates issues such as observer programmes, electronic monitoring and the assessment of bycatch rates in set net fisheries. This information is covered in the Discussion (Section 6).

6. Discussion

6.1 General comments

The methods for testing the efficiency of mitigation techniques vary from simulated experiments (Berggren *et al.* 2009; Berrow *et al.* 2008; Soto *et al.* 2012) to implementation and observation in an active fishery (e.g. Alfaro Shigueto, 2010; Brotons *et al.* 2008b; Carretta *et al.* 2008; Hamer *et al.* 2011). Regardless of the type of experiment conducted, it is important to test mitigation techniques independently of one another so as not to confound interpretation of results (Carretta *et al.* 2008; Larsen *et al.* 2007). Those studies that worked under simulated conditions did not generally test methods in a realistic context and so the behavioural response of bycatch species may not necessarily represent the response to a real fisheries scenario. Testing in an active fishery provides the additional benefit of determining the practicality of mitigation techniques. In fisheries where bycatch levels are relatively low however, scientifically robust mitigation trials may be costly, as large sample sizes would be needed in order to gain enough statistical power to determine effectiveness (Dawson *et al.* 2013). Success in detecting a change in bycatch is highly affected by the scale of the study, with larger sample sizes having greater power to detect real change. Those few studies that conducted power analyses in order to determine the necessary sample size, generally had unequivocal results that were more likely to represent true bycatch rates (Alfaro Shigueto, 2010; Price & van Salisbury, 2007). Carrying out such analyses before undertaking a study of mitigation technique efficiency should be a priority (Dawson *et al.* 2013).

In order to assess efficacy of any mitigation technique it is necessary to have a clear, quantitative conservation goal (Dawson *et al.* 2013; Read 2013). Setting a target for bycatch in the form of PBR (Potential Biological Removal), aims to guide the necessary protection for a species in order to ensure population recovery. PBRs have been previously calculated for Hector's and Maui's dolphins and have been found to be very low at less than one individual per year for most areas (Slooten & Dawson 2010). Overall, current estimated bycatch is on the order of 10-35 times higher than these PBR levels, and in some areas it is much higher. Maui's dolphin current bycatch has been estimated at five individuals per year by an expert panel, which is about 75 times higher than the PBR of one individual every 10 to 24 years (Slooten 2013). With such small PBRs the management goal should be to reduce bycatch to as close to zero as possible for such high risk populations.

6.2 Spatial and temporal closures

One of the main approaches to reducing bycatch is to implement changes to fishing effort that decrease overlap with the habitat of threatened species (*e.g.,* Goldsworthy *et al.* 2010; Hamer *et al.* 2013). Understanding the ecology, behaviour and movements of species at risk of entanglement will therefore allow for more effectively designed closures, which minimise both overlap and unnecessary costs to the fishery. In the case of controversial closures for sea turtles in Pamlico Sound, North Carolina, modelling of species distribution and fishing effort demonstrated that current seasonal closures provided the necessary protection to decrease bycatch levels (McClellan *et al.* 2009). Studies have shown however, that when closures are in place, fishing effort should be removed completely rather than displaced to remaining areas, if overall bycatch reduction is to be achieved (Goldsworthy *et al.* 2010; Slooten 2013). While this redistribution of displaced effort can be factored into modelling, it is not always done as it not always clear where the redistribution will occur. However, it is a critical step in assessing the benefits and impacts of any closures and is important for management agencies in making management decisions. Closures that do not protect key habitat areas are costly for fisheries and of little benefit to bycatch species (Hamer *et al.* 2011, 2013; Niemi *et al.* 2013. If fishing areas are to remain open then conservative bycatch limits are necessary (Hamer *et al.* 2011), but this comes with associated costs. In order to ensure limits are adhered to, high levels of observer coverage and appropriate enforcement are needed (Hamer *et al.* 2011; Kindt-Larsen *et al.* 2011).

While a compromise between conservation and fisheries is the best outcome, it is not always possible to achieve, particularly in cases where the loss of one animal could threaten the survival of the population

(Hardy *et al.* 2012; Slooten 2013). For such situations, even the risk of bycatch during a trial of mitigation techniques is unacceptable, as is the case for Maui's dolphins (Dawson *et al.* 2013) and vaquita (Morzaria-Luna *et al.* 2012). In order to prevent the extinction of the vaquita, recent studies have predicted that all nets would need to be removed from the species' distributional area (Morzaria-Luna *et al.* 2012; Rojas-Bracho & Reeves 2013). Spatial and temporal closures can therefore be costly to fisheries and can be contingent on the provision of economic alternatives and compensation to fishers who rely on fisheries for income and/or food.

As a general rule, spatial closures are more commonly applied than seasonal closures but both have been used successfully. In general, it appears that spatial closures are applied when required levels of bycatch reduction are high as they are more effective in achieving this. Spatial closures can be effective but rely on a solid and detailed understanding of the fishery and the protected species being caught. They are effective when the species to be protected is migratory with a predictable and consistent temporal and spatial distribution and where the distribution of the prey species of the fishery doesn't overlap completely with that of the protected species.

The most obvious negative effect of closures is the resulting impacts on fisheries. The issue of balancing increased protection of threatened species against a reduction in commercial fisheries must be a management decision. However, in considering the potential trade-offs it is essential to have a clear management goal in mind such as reducing bycatch to some specified amount or allowing a certain level of fishing effort to continue. Once the management goal is clearly articulated, then it is possible to scientifically model the effectiveness of closures in order to meet it and then move to make informed management decisions. A wealth of examples demonstrate, however, that the application of closures will most likely be a contentious political and media issue for fishers and conservationists, and that science will only ever be one of the deciding factors. However, if the science is reliable and robust, it can be a very effective instrument in aiding decision makers to achieve good conservation as well as fishery outcomes.

6.3 Acoustic deterrents

Another approach to reducing entanglement is to change the behaviour of bycatch species around fishing nets. The use of acoustic deterrents, particularly 'pingers', has become a common mitigation technique in several fisheries. Dawson *et al.* (2013) reviewed the use and effectiveness of pingers, and found varying levels of success, as was the case for the studies reviewed here. Several studies have found the use of pingers to result in significantly decreased bycatch rates, particularly concerning harbour porpoise (Northridge *et al.* 2011; Palka *et al.* 2008). Some success has also been found for bottlenose dolphins (Brotons *et al.* 2008b; Waples *et al.* 2013), while results for common dolphins have been inconsistent (Berrow *et al.* 2008; Carretta & Barlow, 2011). This highlights that results for different species, areas and potentially even different individuals can be variable and difficult to predict. Erbe and McPherson (2012) modelled the acoustic output and sound propagation of pingers in Queensland, Australia, and found that the pingers tested would be detectable by all species examined. They noted, however, that detection of pingers would not necessary result in a behavioural response.

One of the main issues involved with the use of acoustic deterrents is the chance of habituation, where the behavioural response of animals lessens over long-term exposure. The risk of this occurring is likely even greater, if some reward such as prey, is to be gained by ignoring the deterrent. Some long-term studies have found no evidence of this in active fishery scenarios (Carretta & Barlow 2011; Palka *et al.* 2008), while Berggren *et al.* (2009) detected some signs of habituation during their simulated trial. There are concerns that for some species, acoustic deterrents may act as a 'dinner bell', where they are associated with an easy source of food. This is particularly the case for pinnipeds, though evidence for this is uncertain (Carretta & Barlow 2011).

Another potential risk includes habitat exclusion. If pingers are used extensively and repeatedly in preferred habitat areas of bycatch species, there is potential for animals to be denied access to important areas. This is likely to be more of a threat to coastal species such as Hector's and Maui's dolphins, which have small home-ranges to begin with (Dawson *et al.* 2013).

Pingers have appeared to be very effective in reducing beaked whale bycatch (Carretta *et al.* 2008) and these results indicate how sensitive these species are likely to be with respect to anthropogenic sound in general. However, one caveat with this study is that pingers were implemented alongside a range of other mitigation techniques (e.g. time-area closures and gear modifications) and therefore the resulting reduction in bycatch is likely to reflect the full range of mitigation techniques rather than simply the introduction of pingers, although the authors concluded that pingers were the primary reason for the decline in bycatch levels.

There is potential for pingers to increase noise pollution in the environment. Minimising this is one reason for testing and determining the minimum number and spacing of pingers needed to reduce bycatch. Using more pingers than required will not only increase noise pollution unnecessarily, but could greatly increase overhead costs to fisheries and affect practicality (Larsen *et al.* 2013; Northridge *et al.* 2011). Tests of a louder acoustic device on small cetacean bycatch in the UK (Northridge *et al.* 2011) have appeared effective in terms of reducing the number of devices needed, however, whether overall noise pollution has been decreased remains unclear.

While pingers have shown some success in mitigating bycatch, they come with associated costs for fisheries, particularly when used extensively. These devices are relatively expensive in terms of the cost of initial setup and maintenance. As a results of this, even trials of devices can be cost prohibitive. This is particularly the case for fisheries with relatively low bycatch rates, as a large number of sets would need to be conducted in order to gain sufficient statistical power to determine effectiveness (Dawson *et al.* 2013). Several studies have highlighted concern for the robustness of pingers and the extent of their battery life (Alfaro Shigueto 2010; Carretta & Barlow 2011; Hardy *et al.* 2012; Orphanides & Palka 2013; Waples *et al.* 2013). Maintaining a large number of these devices can prove costly in terms of both repairs and downtime (Alfaro Shigueto 2010, Northridge *et al.* 2011; Waples *et al.* 2013). Northridge *et al.* (2011) even reported safety concerns for crew members as pingers become entangled in gear. Overall, acoustic deterrents show promise, particularly for those species that are neophobic and have large home-ranges (Dawson *et al.* 2013). However, there are many potential risks and costs associated with their long-term use that remain to be fully explored.

6.4 Gear and operational modifications

There remains debate around the reasons behind the bycatch of marine mammals, and it is still uncertain whether entanglement occurs because animals fail to detect nets, or whether they simply do not regard them as a threat. Increasing the acoustic detectability of the net itself has several potential benefits over the use of acoustic deterrents. Both noise pollution and habituation become irrelevant, and maintenance is greatly reduced. However, this mitigation technique relies on the assumption that bycatch is a result of failure to detect netting. Recent studies on chemically increasing the acoustic detectability of nets have been limited, and have not provided any evidence of effective bycatch reduction (Bordino *et al.* 2013; Larsen *et al.* 2007, Mackay, 2011). While Larsen *et al.* (2007) detected a decrease in harbour porpoise bycatch, the interpretation of results was compromised by a concurrent difference in net stiffness between treatments. Target species catch was also reduced to such an extent that this did not appear a viable mitigation technique. Chemically treating nets during or after manufacture may also be cost-prohibitive.

The cost of illuminating nets varies depending on the materials and techniques used, but can be relatively high and cost-prohibitive for a fishery with a small profit margin. While studies of this method were limited, there was evidence of bycatch reduction for green turtles with varying effects on the catch of target species (Wang *et al.* 2010). Illumination by chemical light sticks proved to be the most effective for this species, but more research is needed in order to determine the effectiveness for other species, particularly cetaceans, and the practicalities and costs involved.

Several options for modifying gear exist, and a few have been tested with varying success. Hanging ratio can be modified relatively inexpensively, but recent work has found such modifications to provide no reduction to the bycatch of harbour porpoise (Schnaittacher 2010). An increase in net tension, which again is relatively inexpensive to implement, found potential for bycatch reduction of some shark species without affecting target fish catch (Thorpe & Frierson 2009). When testing low-profile nets, Price and van Salisbury (2007) found the bycatch of both turtles and other non-target species to be reduced.

Many of the economic costs involved in these modifications could potentially be offset by a reduction in net damage, through decreased incidental capture of species such as sharks. Net integrity could also be improved in high velocity areas such as tidal and surf zones. Other potential options that require further study are modifications to net height and twine diameter (Northridge *et al.* 2011). Overall, if net modifications are found to be successful in significantly reducing bycatch, they may be able to work concurrently with other mitigation techniques such as closures, which in comparison are very costly to fisheries (Price & van Salisbury 2007).

Other voluntary mitigation techniques such as Codes of Practice (COP) have also been implemented in New Zealand and elsewhere (MPI & DOC 2012). Examples include the MPI-developed COP for amateur set netting and Fishing Industry lead COPs. While COPs can be positive in highlighting the issue, there is no evidence of their effectiveness as a mitigation technique.

6.5 Observers and monitoring

Observations of fisheries can potentially be done in a variety of ways including extensive observer presence on fishing vessels (Waugh *et al.* 2011), use of models to predict bycatch (Orphanides 2009; Goldsworthy *et al.* 2010; Abraham & Thompson 2011; Morzario-Luna *et al.* 2012), electronic monitoring systems (Evans & Malony 2011; ICES 2011) and satellite telemetry (McClellan *et al.* 2009).

High observer coverage is necessary during both trials and maintenance of any mitigation program. Without it, bycatch rates cannot be accurately monitored, compliance cannot be confirmed and mitigation gear cannot be maintained. The level of current observer coverage is often too low to gain a representative estimation of bycatch rate (Carretta & Barlow 2011; Goldsworthy *et al.* 2010; Hamer *et al.* 2011), and lack of enforcement can lead to a lack of compliance with mitigation techniques (Orphanides & Palka 2013). Observer programs are expensive, however, and even with observers on board, bycatch (Goldsworthy *et al.* 2010; Hamer *et al.* 2011, 2013) and gear malfunctions (Carretta & Barlow 2011) can go undetected. Net dropout, where bycaught animals fall from nets before reaching deck, has been found to be a common occurrence (Goldsworthy *et al.* 2010; Hamer *et al.* 2011, 2013), resulting in an underestimation of bycatch mortality.

Observer programmes are widely used to monitor compliance and the ongoing effectiveness of mitigation techniques. A common issue found in many of the studies is the occurrence of mis- or under-reporting, bycatch dropout and the associated underestimation of mortality (e.g. Goldsworthy *et al.* 2010; Hamer *et al.* 2011, 2013). In many fisheries, there is a statistically significant difference between the reporting rate derived from data provided by commercial fishers and that from independent observer programmes. This highlights the need for better observer coverage and techniques in order to gain a representative estimation of bycatch (*e.g.* Goldsworthy *et al.* 2010; Hamer *et al.* 2011, 2013). There is little doubt that lessons from independent observer programmes overseas have relevance to New Zealand fisheries.

A proportion of fishing is conducted by vessels too small to accommodate observers and so mitigation compliance and efficacy cannot be evaluated easily for this proportion of the fishery (Carretta & Barlow 2011). Electronic monitoring systems have been implemented in some areas in an attempt to increase observer coverage (Hamer *et al.* 2013). However, the accuracy and practicality of such systems has rarely been tested and so their use may be premature. Investigations into the potential for closed-circuit television cameras to remotely monitor bycatch of harbour porpoise have been carried out in Denmark (Kindt-Larsen *et al.* 2011). They found this electronic system worked well on all vessels tested and was much more cost-effective than observer programs. The system also gave more reliable results, as although there was potential for the cameras to miss bycatch events due to dropout underwater, the chance of not detecting bycatch was greater for observers. A major concern with such systems is the time needed for footage analysis. While automatic recognition of marine mammals may be possible, it is very difficult to implement successfully.

With respect to New Zealand, the observer program was established by the Department of Conservation in order to document bycatch and target species catch rates in the New Zealand commercial set net fishery. Relative to the amount of fishing effort, observer effort has been generally low (e.g. less than 1%) across the fishery, with no observers on board fishing vessels between 2001 and 2005 (Abraham & Thompson 2011). There was a two-fold increase in the amount of fishing activity observed from the 2007-08 season to the 2008-09 season. In addition, in 2010, observer effort was increased, being both more spatially focused and temporally spread (Ramm 2011). However, observer coverage is lower than what would be required to make effective and statistically robust conclusions about the magnitude and nature of bycatch. It is therefore unlikely that the observed bycatch rates are representative of total bycatch of marine species in the commercial set net fishery (Abraham & Thompson 2011), not to mention the recreational set net fishery.

7. Relevance and applicability of research to New Zealand

The majority of the studies reviewed in this report provide relevant information that should be taken into consideration during an assessment of potential mitigation techniques for New Zealand. The lessons learnt from overseas studies are useful in informing decisions for New Zealand but there is consistent and compelling evidence that results from one study cannot be assumed to be directly applicable to another fishery or protected species. There are examples of studies of mitigation techniques with a combination of positive, neutral and negative outcomes and so it would be naïve to assume that they will work in New Zealand. That does not mean that these studies should not be used to guide future research and management options for New Zealand as they clearly have value when reviewing candidate mitigation techniques. Another complexity that is not always readily apparent is that the terms gill net and set net are used very broadly for a wide variety of fishing methods often reflecting quite different gear configurations, target species and operational behaviours and, therefore, while a gill net in California may have achieved positive bycatch reduction, it is a very different type of fishery to set nets in New Zealand. Despite this, key lessons about mitigation from other fisheries can be useful in suggesting mitigation solutions for New Zealand.

Perhaps the most common mitigation techniques currently being applied within New Zealand are spatial and temporal closures. A review of similar closures applied elsewhere found, in several cases, that current management offers inadequate protection, as bycatch species regularly travel outside of protected areas (Goldsworthy *et al.* 2010, Hamer *et al.* 2011, 2013). The severity of bycatch risk to several of the species studied (Hardy *et al.* 2012; Morzaria-Luna *et al.* 2012; Niemi *et al.* 2012) is also comparable to that of Maui's dolphins, in that the loss of any individual will significantly impact the survival potential of the population. The outcomes of spatial management were found to vary for individual fisheries (Morzaria-Luna *et al.* 2012) and such mitigation techniques were at times, highly controversial (McClellan *et al.* 2009; Niemi *et al.* 2012) as has also been the case in New Zealand. Modelling procedures to assess spatial correlation in fishing effort and bycatch species habitat use were beneficial in such controversial cases, as they assisted in determining the appropriate scale of current or proposed fishing closures. Given New Zealand's experience with closures, results from overseas are informative as to the potential effectiveness of closures but again, the research highlights that any results will likely be species- and area-specific.

Pingers are the most widely researched form of bycatch mitigation in set nets. Some pingers have been trialled in New Zealand fisheries (Stone *et al.* 1997, 2000; Dawson & Lusseau 2005) and had mixed results. Despite this, pingers are already being used under voluntary Codes of Practice by some commercial fishers. A recent review by Dawson *et al.* (2013) found that there was no evidence that Hector's dolphins were physically displaced from moored pingers but avoidance reactions were observed in 66% of nearby dolphin groups when a pinger was immersed from a drifting boat. However, this latter result was questioned in that boat-based trials may provide poor measures of responses to pingers given the possible confounding effect of the vessel, the potential for dolphins to be startled by the sudden onset of pinger sounds at close range (*sensu* Teilmann *et al.* 2006), and that they do not mimic the behavioural context associated with nets that are actively fishing (Dawson *et al.* 2013).

Pingers appear most successful for cetaceans that are neophobic (i.e. fear of anything new) or easily startled, and have larger home-ranges (Dawson *et al.* 2013). Therefore they are more likely to be effective for phocoenids (i.e. porpoises) than coastal delphinids, and it is unreasonable to expect that pingers will work with all small cetaceans. Pingers are, therefore, likely to be a less effective mitigation technique for Hector's and Maui's dolphins. An equally important consideration is that, with the possible exception of beaked whales for which bycatch has been eliminated, even if pingers are able to deter Hector's or Maui's dolphins, what level of bycatch reduction could be achieved? The required reduction for Maui's dolphins would need to be 100% and a similarly high level would need to be achieved for Hector's dolphin (Slooten 2013). Based on the available evidence it seems that attaining these levels with the use of pingers alone is not presently feasible. Dawson *et al.* (2013) highlight that the risk to these populations of even undertaking a trial could be significant given sample sizes that would be required to demonstrate their effectiveness.

MPI & DOC (2012) recently reviewed the use of pingers as a mitigation technique for Maui's dolphins and arrived at the following conclusion:

> *The use of pingers to reduce interactions between Hector's dolphins and set nets has been investigated and MPI considers the efficacy of these devices to be unproven for Maui's dolphins. Pingers have proven to be effective for some cetacean species but have not been conclusively established as effective for Maui's or Hector's dolphins. It is also not known what undesired impacts pingers may cause, for example exclusion of the Maui's dolphins from their natural habitat and foraging areas. MPI considers any benefits these devices would provide to be unknown and unclear, which could result in unnecessary costs being imposed on industry. If the use of pingers was required off the WCNI [West Coast North Island], data collection on the efficacy of this practice would also be required. However, such data collection is unlikely to be feasible given the small population size of Maui's dolphins. Requiring the use of pingers alone would not be sufficient to determine whether or not pingers are effective in reducing the risk of fishing-related mortality from set nets.*

Recent studies involving net modifications have often had mixed (Larson *et al.* 2007) or no success (Mackay 2011; Schnaittacher 2010) in reducing bycatch. Those chemically modifying the acoustic detectability of nets, have found such techniques to have no effect on the bycatch of small cetaceans (Bordino *et al.* 2013; Larson *et al.* 2007; Mackay 2011). This method relies heavily on the unproven assumption that failure to detect nets is a key reason behind animal entanglement, highlighting the importance of increasing our understanding of why bycatch occurs. There has been some evidence of bycatch reduction for turtles (Price & van Salisbury 2007; Wang *et al.* 2010), sharks and other non-target species (Thorpe & Frierson 2009) through physical net modification. Therefore while there may be some potential in testing these techniques in New Zealand waters, for sharks in particular, the evidence to date for their application to New Zealand is limited and would be speculative at best.

8. General Conclusions and Recommendations

8.1 Overview

Perhaps unsurprisingly, the conclusions from this review are similar to those of the previous CSP reviews by Bull (2007b) and Rowe (2007), as well as the recent global review by Waugh *et al.* (2011). This consistency in conclusions primarily reflects a lack of new approaches or techniques being introduced into the field of bycatch mitigation and a stronger focus on refinement or additional testing of existing methods.

The overall conclusions of this review can be summarised simply: there is no silver bullet for mitigation of protected species bycatch and no single method will work in all fisheries, for all areas, all species and at all times – therefore species- and fishery-specific solutions need to be explored.

The effectiveness of mitigation can only be determined when clear management goals are identified, quantified and articulated. For example, a mitigation technique could be considered an effective tool if it reduced the bycatch rate by 10%, if that was the management goal. Furthermore, a protected species goal could be tied in with a fisheries management goal such as, any mitigation technique implemented would not reduce the total landed catch by more than 10%. Obviously, in this instance for any technique to be effective it would have to meet both goals in this example.

Globally, mitigation has focused on four main areas: acoustic deterrents, spatial and temporal closures, gear modifications and operation modifications. Over half of the literature reviewed was related to acoustic deterrents, over a quarter spatial and temporal closures, and the remainder split between gear and operational modifications.

8.2 Acoustic deterrents

Acoustic deterrents have been tested on a wide range of cetacean species with results varying considerably. They have been most successful for beaked whales, achieving a 100% reduction in bycatch in the California drift net fishery (when implemented in conjunction with other mitigation techniques). In addition, four species (harbour porpoises, franciscana, striped and common dolphins) have shown unequivocal, significant reductions in bycatch and/or clear avoidance of pinger sounds. For other species, the evidence is somewhat contradictory. The mechanism for deterrence is unclear but is likely to vary by species and is most likely caused by individuals avoiding pingers but there have been some conflicting results across studies. Positive outcomes of pinger mitigation can include decreased interactions with nets, and subsequent decreased levels of bycatch and net damage, and increased target catch rates. Negative outcomes can be no change to bycatch levels, decreased effectiveness over time, decreased target catch, potential habitat exclusion, increased noise pollution and gear reliability problems. Pingers appear most successful for cetaceans that are neophobic (i.e., fear of anything new) or easily startled and have larger home-ranges (Dawson *et al.* 2013). Therefore they are more likely to be effective for phocoenids (i.e. porpoises) than coastal delphinids, and it is unreasonable to expect that pingers will work with all small cetaceans. Due to the small home-ranges of Hector's and Maui's dolphins, pingers are unlikely to be effective and their extensive use may pose a greater risk of habitat exclusion. Pingers are mandatory in some fisheries (e.g. Gulf of Maine gillnet fishery, California drift net fishery) and have been used in New Zealand under an industry led Code of Practice.

8.3 Spatial and temporal closures

Spatial and temporal closures are the most effective mitigation technique but essentially remove fishing from the area or period in question. They are especially effective solutions in areas and/or at times when protected species only occur in a small component of a fishery. The potential benefit (to protected species) and loss (to fisheries) is best explored through the use of spatial and temporal modelling scenarios for protected species and fisheries. While this approach has proven to be effective at quantifying benefits and losses, it can require considerable data, which is generally unavailable. This modelling approach also requires clear management goals for both protected species and fisheries upon which to gauge the impact of the proposed closures. Closures have been used widely across the world including in New Zealand, Australia, USA, the European Union and Mexico. While these closures can lead to loss of fishers' livelihood and supply of food, financial compensation has been used to offset losses to fishers from closing areas. One concluding note is that while closures have the potential to be highly effective in reducing bycatch on paper, the reality is that without the commitment of fishers, complemented by effective compliance monitoring and enforcement, they may be no better than any other mitigation technique.

8.4 Gear and operational modifications

Surprisingly little attention was given in the literature to gear and operational modifications. The primary techniques for gear modification included making nets easier to detect acoustically (e.g. for cetaceans) or visually (e.g. for turtles). There have been conflicting results in trials to make nets more acoustically detectable; when bycatch was reduced so was the target catch rate. Trials for increasing the visual detectability of nets have shown good results for the reduction in turtle bycatch. Operational modifications included changing net hanging ratio, increasing net tension, using tie downs and implementing Codes of Practice. While there has been some evidence of reductions in bycatch, these have generally also been associated with reductions in target catch although the sample sizes for all of these trials are small with low statistical power. Codes of Practice have been voluntarily implemented by some fisheries for bycatch reduction and while there are some anecdotal reports of the effectiveness of these, in general, there are no statistical analyses to support these claims.

8.5 Areas for future research

There is no single mitigation technique that eliminates bycatch while maintaining fish catches in all fisheries, for all areas, all species and at all times. However, of the techniques reviewed, two have the most research potential for application to New Zealand set net fisheries. These are outlined below and recommendations of future research are provided in Section 8.6.

- Spatial and temporal closures:
    - MPI and DOC have implemented these in order to mitigate bycatch of Hector’s and Maui’s dolphins;
    - Excellent evidence of effectiveness in reducing bycatch levels for all protected species when implemented at an appropriate scale;
    - Trade-off is that fishing is prohibited, but this may be partly addressed by financial compensation to fishers in appropriate circumstances;
    - Must be driven by clear management goals for protected species and fisheries, and be thoroughly evaluated against them;
    - **Conclusion: spatial and temporal closures are the mitigation techniques most likely to be effective in reducing the bycatch of protected species in set nets in New Zealand.**
- Acoustic deterrents (i.e. pingers):
    - While achieving variable success rates across species, there have been some significant examples of large reductions in bycatch;
    - There have been some pinger trials with Hector’s and Maui’s dolphins, but these have led to equivocal results;
    - Pingers appear most successful for cetaceans that are neophobic (i.e. fear of anything new) or are easily startled and have larger home-ranges. They are, therefore, more likely to be effective for phocoenids (i.e. porpoises) than coastal delphinids. As such, pingers are unlikely to be effective mitigation techniques for Hector’s and Maui’s dolphins;
    - Prior to any possible trials, the effectiveness of pingers must be evaluated against:
(i) What reductions in bycatch may be achievable, and will this meet management goals?; and
(ii) What sample sizes would be necessary in order to yield sufficient statistical power to quantify effectiveness?;

- If pingers are implemented, dedicated enforcement and compliance monitoring regimes will be required, as well as high levels of observer coverage to assess long-term effectiveness;
- **Conclusion: While pingers have shown to be effective in some fisheries overseas, they are unlikely to be effective mitigation techniques for Hector's and Maui's dolphins or other protected species in New Zealand.**

8.6 Recommendations for future research

Based on an assessment of the mitigation techniques reviewed, we make the following recommendations for future research on the mitigation of protected species bycatch in New Zealand set net fisheries:

- The most effective form of protected species bycatch mitigation is spatial and temporal closures. In order to ensure that management decisions are based on robust and reliable data, research should focus on the development of quantitative models that can assess the likely impacts of closures on both bycatch rates and fisheries. Such models are likely to be data intensive if they are to be reliable and robust. They should also include consideration of the displacement of fishing effort from closed areas and the impact of this on overall bycatch levels;
- In order to assess the effectiveness of any mitigation technique it is essential that a target for bycatch reduction be developed. This could take the form of a Potential Biological Removal (as has been already applied to Hectors and Maui's dolphins) or some other metric that is relevant to the protected species;
- For species that already have Potential Biological Removals, these should be reviewed in light of the scale of known or estimated set net mortality and assessments made of the potential costs and benefits of spatial or temporal closures;
- Any research into the mitigation of bycatch in set nets should include an assessment of effectiveness for both commercial and recreational set netting; and
- There has been little research on mitigating the bycatch of protected species other than dolphins and this is an area for future work, including potential work on shearwaters, penguins and shags.

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10. References reviewed and/or cited

Note: This list contains 79 papers reviewed for relevance to set net mitigation techniques. Of these, 35 were reviewed in depth and are reported in Appendix 1. In addition, it also contains additional references that have been cited in the body of this document.

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Appendix 1:

Summary table of set net literature that provides details of mitigation

No	Mitigation Technique	Source	Region of Interaction	Gear configuration	Target fish species	Bycatch species	Level of efficacy	Level of scientific rigour	Caveats or uncertainties in methods
1	*Acoustic deterrents*	Alfaro Shigueto 2010	Salaverry, Northern Peru	Surface drift gill net	Sharks	Harbour porpoise (*Phocoena phocoena*), Burmeister's porpoise (*Phocoena spinipinnis*), Dusky dolphin (*Lagenorhynchus obscurus*), Bottlenose dolphin (*Tursiops truncatus*), Common dolphin (*Delphinus capensis*)	Fishing sets with pingers reduced bycatch of small cetaceans by at least 73% in relation to control nets but did not eliminate it completely. 69% of control trips had bycatch compared to 25% of trips using pingers. Catch rate of target sharks appeared unchanged.	Assessed the effect of pingers on small cetacean bycatch under true fishing conditions in a small artisanal fishery. One control vessel and one vessel using pingers participated. A power analysis was used to determine necessary sample size for detecting between 50-90% bycatch reduction. A total of 71 control sets and 49 pinger sets were conducted.	Not peer reviewed. Reduction in bycatch not significant at 5% level unless one trip with usually high bycatch despite using pingers is treated as an outlier. Analysis of target species catch is preliminary with no statistical analysis. Bycatch results are not specific to individual species.
2	*Acoustic deterrents*	Berggren *et al.* 2009	West Scotland	Demersal gill net	None. Simulated	Harbour porpoises (*Phocoena phocoena*)	Pinger sound significantly reduced the echolocation rate by 50-10% and reduced the sighting rate of harbour porpoise at a greater spatial range than previously known. Return time of porpoises to previously ensonified areas increases with longer exposure to pinger sound. Habituation was detectable at 2 of 9 acoustic click detectors (PODs) even though pingers were only used intermittently.	Moderate sample size. Survey period of 50 days using one simulated net in each of two bays. Use PODs to passively monitor echolocation rates around nets. Observations of porpoise behaviour were from land using a theodolite.	Differences in results between this study and a similar one in 2001 confirm it is important to replicate pinger studies in both time & area. Study was conducted using two simulated nets, not an active fishery. As no fishing actually took place, this may not be representative of harbour porpoise behaviour around actual gill nets.
3	*Acoustic deterrents*	Berrow *et al.* 2008	South coast of Ireland	Gill net	None. Simulated test	Common dolphin (*Delphinus delphis*)	Results suggest pingers may not consistently be effective in deterring common dolphins. No evasive responses were consistently observed during pinger use.	Tests the efficacy of 6 different pinger brands on deterring common dolphins over a total of 45 tests and 3 different trials. A range of age-classes were sampled.	Pingers were tested from a small vessel while dolphins were bowriding and foraging. The presence of the vessel may have affected results, compared with testing on independent nets. Lack of movement away from the vessel at the time of pinger activation does not necessarily mean dolphins would seek to interact with pingered-nets in an active fishery. Sample size was also low, and the same group of dolphins was sometimes subjected to a number of consecutive tests.
4	*Acoustic deterrents*	Brotons *et al.* 2008b	Balearic Islands, Spain	Demersal gill net	Various	Bottlenose dolphin (*Tursiops truncatus*)	Net interaction rates were significantly reduced by 49% with active pingers, but not all brands were equally effective. Catch yields were increased by 9% with active pingers, though not significantly.	Large-scale experimental study of pinger effectiveness in an active fishery. 1193 fishing operations observed, trailing three pinger brands. Statistically analysed results with reasonable power. Pinger treatments were assigned so as to minimise effect of geographic area and both observers & fishers were blind as to the type of pingers on their vessel.	Longer-term study required as there is potential for habituation. Pinger acoustic properties were not verified. All types of dolphin interactions with nets were used as a proxy for risk of fatal entanglement.
5	*Acoustic deterrents*	Buscaino *et al.* 2009	Sicilian Channel, Egadi Isles, Italy	Demersal gill net	None. Simulated	Bottlenose dolphin (*Tursiops truncatus*)	The net equipped with pingers contained 28% more fish biomass and was less damaged.	Low sample size and statistical power. Non-fishery experiments to assess pinger effectiveness. Twenty-nine hauls in total, each consisting of a pinger net and control net.	Cause of net damage assessed subjectively. Fishers determined whether holes were caused by dolphins, rather than fish, vessel or seafloor contact, or other operational factors.
6	*Acoustic deterrents*	Carretta *et al.* 2008	California Current, USA	Drift gill net	Swordfish, Sharks	Beaked whales	Beaked whale bycatch dropped from 33 beaked whales in 3303 sets during the first 6 years of the	Large dataset. Pinger effectiveness assessed for a 16 year fishery observer program. Pingers were	Other mitigation measures introduced throughout the same time period include a

No	Mitigation Technique	Source	Region of Interaction	Gear configuration	Target fish species	Bycatch species	Level of efficacy	Level of scientific rigour	Caveats or uncertainties in methods
							observer program, to none in 4381 sets over the last 10 years while pingers were in use. Results suggest beaked whales may be among the most sensitive cetacean taxa to pinger frequencies.	introduced as a mandatory mitigation measure for the last 10 years, with each net containing at least 40 pingers. Statistical tests of whether bycatch decrease was due to chance alone found that to be extremely unlikely.	mandatory increase in max. fishing depth and a seasonal area closure, shifting fishing effort south. However it is explained that these are unlikely to be the reason for reduced beaked whale bycatch. It is uncertain whether bycatch reduction could be due to decreased whale abundance. Recent abundance surveys have had unfavourable weather conditions and low abundance estimate precision.
7	*Acoustic deterrents*	Carretta & Barlow 2011	California, USA	Drift gill net	Swordfish, Thresher shark	Common dolphin (*Delphinus delphis*), California sea lion (*Zalophus californianus*)	Common dolphin bycatch rates on sets with ≥30 pingers were nearly 50% lower than those without pingers. For California sea lion however, pinger nets had almost twice the bycatch rate. There was no evidence of pinger use being linked to pinniped depredation of fish catch so pingers do not appear responsible for the increase. An increase is sea lion abundance is the more likely explanation. Bycatch of other cetaceans was not significantly affected by pinger use, however sample sizes were small. Beaked whales were not observed bycaught since 1 year prior to pinger use. Bycatch was 10x greater when >1 pinger failed. Over 14 years there was no evidence of habituation.	Large dataset. Data on fishing gear, environmental variables and bycatch rates were recorded over 8,000 sets by fishery observers over a period of 19 years. During the last 14 years, over 4,000 sets were fitted with pingers. Sample size for examining the effect of pinger failure was small. Attempts were made to standardise sets used in analyses for variables such as mesh size, net length and soak time.	More than one pinger failed in 3.7% of observed sets. In those cases where pinger failure rate was recorded, this was found to occur for ~18% of deployed pingers. Observers sometimes failed to detect non-functioning pingers, so this failure rate is likely greater than recorded. An increasing fraction of fishing Is conducted by vessels too small to accommodate observers. Pinger compliance and effectiveness could not be evaluated for this portion of the fishery, potentially biasing results.
8	*Acoustic deterrents*	Dawson *et al.* 2013	Various	Gill net	Various	Various small cetaceans	Overall, pingers show promise for neophobic species with large home ranges. Significant reductions in bycatch of harbour porpoise, Franciscana, common dolphin, striped dolphin and beaked whales have been demonstrated. Two long-term studies show no sign of habituation. Studies on depredation mitigation show small, inconsistent improvements in fish catch and some reduction in net damage. Have been particularly successful for harbour porpoise, with large reductions in bycatch over much of the species' range using a variety of pinger types. Unreasonable however, to expect similar success for all species. Several risks remain, such as habitat exclusion for species with restricted ranges. Small-scale fisheries in the developing world are also unlikely to have economic resources to implement this mitigation method. Necessary to have a target for bycatch reduction as without a quantitative goal it is not possible to assess efficiency. Power analyses should be used to determine sample size needed to detect meaningful effects.	Reviews studies on pingers as tools to reduce small cetacean bycatch in gill net fisheries.	Some literature reviewed was unpublished, though data were critically assessed before inclusion in this review.

No	Mitigation Technique	Source	Region of Interaction	Gear configuration	Target fish species	Bycatch species	Level of efficacy	Level of scientific rigour	Caveats or uncertainties in methods
9	*Acoustic deterrents*	Erbe & McPherson 2012	Queensland, Australia	Gill net	None. Simulated test	Humpback whale (*Megaptera novaeangliae*), Indo-Pacific bottlenose dolphin (*Tursiops aduncus*), Bottlenose dolphin (*Tursiops truncatus*), Indo-Pacific humpback dolphin (*Sousa cinensis*), Common dolphin (*Delphinus delphis*), Australian snubfin dolphin (*Orcaella heinsohni*), Dugong (*Dugong dugon*)	Pingers tested were found to be detectable by all species and were installed at appropriate spacing to highlight the net to all animals travelling parallel or perpendicular to the net.	Aims to estimate ranges and regions over which pinger sound is detectable by marine mammals in the Gold Coast marine environment. Modelled acoustic output and sound propagation of pingers. Measured ambient noise levels. Demonstrates how to estimate maximum pinger spacing depending on animal swimming speed. Small sample size (tested 3 pingers of each type).	Had to make inferences about the hearing capabilities and sensitivities of some species in the absence of direct hearing measurements. Estimated based on reported behavioural responses, anatomical studies and measurements of relative species. Pinger output varied with individual pingers and direction. The sound propagation model will vary with temperature, time of day and season. Did not estimate behaviour responses. For a sound to induce a behavioural change the received level may have to be larger than the detection level.
10	*Acoustic deterrents*	Gazo *et al.* 2008	Balearic Islands, Spain	Trammel net	Red mullet	Bottlenose dolphin (*Tursiops truncatus*)	Pingers did not prevent dolphins approaching nets, but those nets equipped with active pingers received 87% less damage. Predation in nets reduced by ~50% with pinger use. No significant effect on target species catch.	Small sample size. 55 nets monitored in total (27 with active pingers, 16 with non-functioning pingers, 12 with no pingers). Bottlenose dolphin presence reported around 7 of the 55 net sets.	Results on dolphin interaction based on net or catch damage is likely biased. Not clear such damage is caused by dolphins, rather than operational procedures and contact with rocky seafloor. Fishers were not consistent in attributing damage to dolphin interaction.
11	*Acoustic deterrents*	Gönener & Bilgin 2009	Sinup Peninsula, Black Sea	Demersal gill net	Black Sea turbot (*Schophthalmus maeoticus*)	Harbour porpoise (*Phocoena phocoena*)	Pingers significantly reduced bycatch. Target fish catch rate increased with pinger use though fish size was not affected.	Low sample size and statistical power. Pinger and control nets were compared on 20 fishing trips. Further sampling should be carried out over a greater scale and time period to determine the risk of habituation.	No quantitative data on bycatch rate in this area prior to the study.
12	*Acoustic deterrents*	Hardy *et al.* 2012	Cornwall, UK	Demersal gill net, trammel net	Benthic species (e.g. monkfish)	Harbour porpoise (*Phocoena phocoena*), Bottlenose dolphin (*Delphinus delphis*)	Pingers resulted in a 35-51% decrease in harbour porpoise echolocation.	Moderate sample size. Only four porpoise and no dolphin bycatch was recorded. C-POD acoustic detectors used to passively assess the response of cetaceans to pingers.	Habituation could not be tested using the pingers on fishing nets, as the location of nets was not controlled. Pingers were moored at two sites, however too few detections were made at one to detect any potential habituation, and trends may be confounded with seasonal patterns. Reduced response to pingers where background noise was louder, but this may be due to pinger failure. 7 of the 23 pingers were found to be inactive but the time of failure is not known as the pingers were not tested during the trial. Assumed loud clicks indicated animals close to the CPODs. Not possible to infer the extent of porpoise displacement by the pinger. Loudness of clicks did not vary with pinger presence and porpoises can vary the sound pressure level of clicks over a wide range.
13	*Acoustic deterrents*	Larsen *et al.* 2013	Danish North Sea	Gill net	Various	Harbour porpoise (*Phocoena phocoena*)	Pinger use significantly decreased bycatch rate. When spaced at 585 m bycatch was reduced by 78% compared with 100% reduction when spaced at 455 m. 50 porpoises caught in total, of which 45	Controlled experiment testing optimal pinger spacing for bycatch reduction. Compared control nets with no pingers to those with two different pinger spacings (455 m and 585 m) which increase	Data on target species catch only recorded on 27 of 108 hauls. Statistical comparisons of this could only be carried out between control nets and one of the tested spacings

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							were caught in nets with no pingers. No statistical difference in target species catch, though limited data on this.	spacing from the current regulations (max. 200 m). Relatively small sample size of 5 fishing trips over 21 days, with a total of 108 hauls observed.	(455m).
14	*Acoustic deterrents*	Northridge *et al.* 2011	UK	Gill net	Various	Harbour porpoise (*Phocoena phocoena*), Common dolphin (*Delphinus delphis*)	Initial analyses suggest that Dolphin Dissuasive Devices (DDDs) may be heard 2km away while other pingers only reach 100-200m. Nets with DDDs caught significantly fewer porpoises (63-66%) but no significant difference in bycatch rate of dolphins. This reduction in porpoise bycatch is less than reductions reported for pingers (80-95%), however DDDs were more widely spaced. None of the bycatch in nets occurred within 1.2km from the nearest DDD.	Tests the effectiveness of Dolphin Dissuasive Devices (DDDs) on reducing bycatch to determine if a few of these louder deterrent devices may be sufficient compared to the many pingers currently in use. Overall, relatively small sample size. Observations on DDD trials from 15 vessels, each making 1-18 trips.	Data are difficult to interpret. Did not concurrently compare DDDs with pingers during the same study. Sample size of dolphin bycatch is too small to be confident that it represents true bycatch levels.
15	*Acoustic deterrents*	Palka *et al.* 2008	NE Atlantic, USA	Not specified but mostly sink gill nets in area	Various	Harbour porpoise (*Phocoena phocoena*)	Bycatch rates in hauls without pingers were greater than those with the required pingers. Unexpectedly, when hauls had an incomplete set of pingers, bycatch was greater than those without pingers altogether. As mesh size increased so did bycatch rate, despite the presence of pingers. All observed bycatch was in nets of >15 cm mesh size. No5evidence of temporal trends in bycatch, suggesting no habitation so far.	Large dataset. Bycatch data from over 25,000 gill net hauls observed were examined to determine long-term pinger effectiveness and compliance. Coefficient of variation of bycatch rates was estimated using bootstrapping.	The increased bycatch in hauls with incomplete pingers could be due to several potential confounding factors. By chance, there may have been different environmental/gear characteristics. Harbour porpoise may interpret a gap in pingers as a gap in the net.
16	*Acoustic deterrents*	Soto *et al.* 2012	Moreton Bay and Keppel Bay, QLD, Australia	Gill net	None. Simulated test	Australian snubfin dolphin (*Orcaella heinsohni*), Indo-Pacific humpback dolphin (*Sousa chinensis*)	While movements and behaviour of both species changed subtly, active pingers did not change the likelihood of animals leaving the area. Snubfin dolphins slightly decreased time spent vocalising. Humpback dolphins slightly decreased time spent foraging and the rates of both active surfacing and clicking. Pinger arrays did not change presence or movements of humpback dolphins when observed from land.	Tested surface behavioural and acoustic response of dolphins to pinger use during sequential treatment trials from a research vessel. Relatively small size (17 and 10 trials for humpback and snubfin dolphins respectively). Measured changes in humpback dolphin movements around pinger array in a simulated gill net. Observations were made from land over 20 days. Analysed so as to avoid pseudoreplication.	Pingers were tested from a research vessel. The presence of the vessel may have affected results, compared with testing on independent nets.
17	*Acoustic deterrents*	Waples *et al.* 2013	North Carolina, USA	Demersal gill net	Spanish mackerel (*Scomberomorus maculatus*)	Bottlenose dolphin (*Tursiops truncatus*)	Fish catch was significantly lower when dolphin interactions were observed. Pingers did not affect fish catch, but dolphin interaction decreased and echolocation increased with active pingers. The durability of pingers however, is not sufficient for effective deployment in this fishery.	Moderate sample size. Compared dolphin behaviour and fish catch between 151 sets, 83 with active and 68 with control (non-functioning) pingers. Prior to use, baseline data were collected from 136 sets. Both visual and acoustic observations of dolphins used to evaluate pinger effect.	Number of focal dolphin follows is fairly low. Dolphin depredation of catch not observed often enough to determine whether pinger use affects depredation rates.
18	*Electronic monitoring*	Kindt-Larsen *et al.* 2011	Denmark	Various	Cod (*Gadus morhua*), Plaice (*Plueronectes platessa*)	Harbour porpoise (*Phocoena phocoena*)	Generally worked well. Fishers found it easy to use and only rarely needed technical staff for repairs. Video detected 36 bycaught porpoises while fishers only reported 25. Overall, electronic monitoring gave more reliable results as observers often missed bycatch due to dropout. Also much more cost effective compared to observers. Footage quality was never too low to allow bycatch detection. None of the vessels tested were unsuited for camera observation.	Investigates the potential of closed-circuit television cameras for electronically monitoring bycatch. Only a small number of vessels were equipped with monitoring equipment due to installation costs. Observed six vessels over the course of a year. Cameras placed in view of nets when breaking water's surface. Analysed using software which integrates all cameras and GPS tracks. Video footage viewers were trialled using test videos to test their accuracy. Videos played back at a rate of 10-12 times faster than real time. Computer techniques for	Three bycaught porpoises recorded by fishers not found in video footage. Control system found to be sensitive to unstable power supplies. Bycatch dropout may still go undetected if below water. Birds were detectable, but to record this bycatch video playback would need to be much slower, resulting in greater analysis

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								detecting bycatch tested in MATLAB.	time. Analysis time is a major concern when working with such large video datasets. Computerised montage methods tested were not found to be functional. Automatic recognition for marine mammals is difficult to implement successfully.
19	*Acoustic detectability Gear modification*	Bordino *et al.* 2013	San Clemente, Argentina	Gill net	Striped weakfish (*Cynoscion guatucupa*), White croaker (*Micropogonias furnieri*)	Fransiscana dolphin (*Pontoporia blainvillei*)	No significant difference in bycatch rate or target fish catch rate between net types. These modifications do not appear effective in reducing Fransiscana dolphin bycatch.	Controlled field trial collecting data on effects of 3 net types (stiffened, barium sulphate infused, control) on Fransiscana bycatch. Moderate sample size of 807 hauls in 157 fishing trips observed. Three artisanal boats took part and 77 bycaught dolphins were observed in total. Depth sensors used to quantify the fishing behaviour of nets. Data analysed using generalized linear modelling to assess differences in bycatch and target species catch rates across different net types.	The reflective net was also found to have an 18% reduction in fishing profile compared to the other nets tested.
20	*Gear modification*	Larsen *et al.* 2007	Danish North Sea	Demersal gill net	Various	Harbour porpoise (*Phocoena phocoena*)	Significant reduction in harbour porpoise bycatch rate using iron-oxide (IO) nets (none caught compared to 8 in control nets). However, catch of target cod was also significantly reduced in iron-oxide nets by ~30%. Fish in modified nets were also generally smaller. Tests indicated the acoustic target strength of the two net types was not significantly different. Instead, the stiffness of the nets appears to have caused these different catch rates.	Relatively small sample size. Conducted as controlled experiment comparing bycatch rate of high density iron-oxide gill nets to conventional gill nets. Comparative hauls were restricted in time and space with the aim of minimising natural variation in species availability between hauls.	Control and experimental nets differed in colour and stiffness in addition to the use of iron oxide, confounding interpretation of results. Total length of net fished was only half the effort originally considered necessary. Not known whether failure to detect nets is the fundamental reason for bycatch of harbour porpoises.
21	Gear modification	Mackay 2011	San Clemente, Argentina	Demersal gill net	Striped weakfish (*Cynoscion guatucupa*), White croaker (*Micropogonias furnieri*)	Fransiscana dolphin (*Pontoporia blainvillei*)	No significant difference in bycatch rate or target fish catch rate between stiffened, barium sulphate and control nets. Such modifications do not appear effective for reducing Fransiscana dolphin bycatch.	Data collected on effects of 3 net types (stiffened, barium sulphate, control). Four fishing boats from local artisanal fishery took part. Total of 283 hauls. Sample size too low to have sufficient power to detect a significant reduction in bycatch between three treatments.	PhD thesis – not published. Possible the positioning of nets relative to each other biased bycatch rates. Data too limited to quantitatively assess this.
22	*Visual deterrent Gear modification*	Wang *et al.* 2010	Baja California, Mexico	Surface and demersal gill nets	Various (e.g. flatfish, elasmobranchs)	Green turtle (*Chelonia mydas*)	Shark shapes added to nets significantly reduced bycatch rate by 54% but also reduced target catch by 45%. Nets illuminated by chemical light sticks and LED lights were more effective mitigation measures, significantly reducing bycatch by 60% and 40% respectively, while having negligible impacts on target catch.	Relatively high sample size, conducted over several years. Tested the effect of three visual deterrents on bycatch and target species catch rate.	Bycatch and target species catch trials were assessed in two different areas.
23	*Hanging ratio Operational modification*	Schnaittacher 2010	Gulf of Maine, New England, USA	Gill net	Finfish	Harbour porpoise (*Phocoena phocoena*)	On average, nets with a hanging ratio of 0.33 caught more important finfish species than the 0.50 hanging ratio. There were no apparent patterns in marine mammal bycatch.	A test of the effect of different hanging ratios on harbour porpoise bycatch. Results presented are preliminary and no statistical analysis has been conducted.	After 19 hauls the gear was reconfigured, affecting the comparability of some data.
24	*Tension Operational modification*	Thorpe & Frierson 2009	North Carolina coastal waters, USA	Demersal and sinking gill net	Spanish mackerel (*Scomberomorus maculatus*), Spot (*Leiostomus*	Sharks	No significant difference in catch rate of target species between control and modified gill nets, while bycatch rates of some shark species were significantly reduced due to modifications. This	Fairly small sample size. Control and modified gill nets of three stretch sizes were compared to test the effects of increasing net tension on shark bycatch and target fish catch.	Gill nets were selecting sub-adult specimens of species, violating model assumptions.

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					xanthurus)		was particularly the case for those shark species for which wrapping was the primary mode of entanglement.		
25	*Profile*	Price & van Salisbury 2007	Pamlico Sound, North Carolina, USA	Demersal gill net	Various	Marine turtles	Sea turtle interactions were effectively reduced and target catches acceptably maintained when testing low-profile gill nets. Total bycatch of other species was also reduced.	Low-profile gill net configuration was tested against standard gill nets to determine this mitigation measure's efficiency in reducing bycatch rate of sea turtles while maintaining target catch. All other characteristics were identical in both net types. Statistical power tests were conducted to determine the appropriate sample sizes and 291 comparison gill net sets were conducted.	
26	*Spatial & temporal closures*	Slooten 2013	New Zealand	Gill net	Various	Hector's dolphin (*Cephalorhynchus hectori hectori*), Maui's dolphin (*Cephalorhynchus hectori maui*)	Population recovery is unlikely under current protection measures. Bycatch rates for S. Island east coast have decreased from 35-46 per year to 23, indicating some effectiveness. However, there is still considerable overlap between fishing effort and dolphin distribution. No evidence of substantial reduction elsewhere, and in the far north and south regions bycatch has increased slightly. Maui's dolphin current bycatch is about 75 times higher than the potential biological removal (PBR). Recommends protection increased to cover all waters <100 m deep including harbours and a protected area between N. and S. Islands.	Reviews the effectiveness of closures in reducing Hector's and Maui's dolphin bycatch. Several independent analyses of population trends have produced consistent results. Compares bycatch rates before and after the implementation of protection measures.	Scientifically robust data on bycatch before and after closures are available only for the South Island east coast population due to limited observer coverage in other areas. Bycatch comparisons elsewhere are instead estimated from opportunistic sightings and strandings.
27	*Spatial & temporal closures*	Goldsworthy *et al.* 2010	South Australia	Demersal gill net	Gummy shark (*Mustelus antarcticus*), School shark (*Galeorhinus galeus*)	Australian sea lion, ASL (*Neophoca cinerea*)	Unsustainable bycatch levels of ASL with current closures. Females forage further offshore in unprotected areas. Potential closure scenarios based on female core foraging areas will provide greatest reduction in bycatch (95%) while minimising closures to the fishery. Fishing effort in closed areas needs to be completely removed, not displaced.	A range of models used to quantify bycatch risk and associated confidence limits. Wide-range of data included from ASL population surveys, satellite tracking, bycatch observer programs, reported fishing effort. Associated assumptions and limitations are discussed in detail.	Underestimation of ASL bycatch rates due to underreporting, net dropout and limited observer coverage (2.4% of fishing effort). Recommend development of electronic monitoring methods. Limited data on ASL demographics, foraging behaviour. Model assumptions could affect results.
28	*Spatial & temporal closures*	Hamer *et al.* 2011	Great Australian Bight (GAB), South Australia	Demersal gill net	Gummy shark (*Mustelus antarcticus*), School shark (*Galeorhinus galeus*)	Australian sea lion, ASL (*Neophoca cinerea*)	A mortality rate of 4-15 individuals killed per breeding cycle within the Marine Park and 14-33 over the larger GAB. These bycatch levels are unlikely to be sustainable and represent minimum estimates due to the high prevalence of net dropout. 75% of mortalities observed were within the Marine Park during the period open to fishing. This raises concern about the effectiveness of current management arrangements. Nine tracked females spent only 27.7% of their time inside the Marine Park. ASLs are therefore at risk not only for the 6 month period open to fishing within the Marine Park, but year-round throughout the wider GAB. Regardless of spatial closures, the fishery has declined considerable since the late 1990s due to collapse of the school shark stock.	Overall small sample size, but the first study to specifically assess the effectiveness of an MPA designed in part to conserve ASLs. To assess bycatch rates 13.1% of fishing effort was monitored across the GAB region. Nine ASLs were tracked to assess at-sea movements.	Net dropout was found to be a common occurrence, meaning the majority of bycaught animals would normally go undetected.

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29	*Spatial & temporal closures*	Hamer *et al.* 2013	South Australia (SA)	Demersal gill net	Gummy shark (*Mustelus antarcticus*), School shark (*Galeorhinus galeus*)	Australian sea lion, ASL (*Neophoca cinerea*)	Current spatial closures are not large enough to reduce significant overlap & prevent bycatch. Some small subpopulations remain at risk. Bycatch limits are being exceeded due to delays in bycatch reporting & processing.	Most comprehensive investigation of ASL at-sea behaviour to date, involving 1.8% of adult females from 16 of 48 breeding sites in SA.	Use of electronic bycatch monitoring is premature as accuracy has not been determined. Net dropout commonly occurs, so majority of bycatch would normally go undetected. Processing of bycatch reports needs to be sped up to ensure limits are not exceeded. ASLs from 32 breeding colonies were not tracked.
30	*Spatial & temporal closures*	McClellan *et al.* 2009	Pamlico Sound, North Carolina, USA	Large-mesh gill net	Southern flounder (*Paralichthys lethostigma*)	Sea turtles (*Caretta caretta, Chelonia mydas, Lepidochlys kempii*)	Current closures were found to be well placed, concurring with reduction in bycatch within the protected area. Model highlighted areas underappreciated as turtle habitat and accurately predicted areas where bycatch occurred, allowing independent identification of high-risk fishing areas.	Hypothesised that bycatch is predictable because of habitat preferences of fishers and marine vertebrates. Used a predator-prey type model to assess spatial correlation of gill nets and sea turtles, and identify areas of high bycatch risk. Tagged 50 turtles representing the area's species diversity and size. Errors associated with turtle positions were filtered out and statistical tests used to examine movement & site-fidelity. Observed 7.6% of fishing effort, stratified over time/space. Model performance evaluated using real bycatch data.	Two satellite transmitters failed immediately. All but two others functioned until turtles migrated out of area or end of fishing period.
31	*Spatial & temporal closures*	Morzaria-Luna *et al.* 2012	Northern Gulf of California, Mexico	Gill net	Finfish	Vaquita (*Phocoena sinus*)	Only scenarios with large spatial closures would lead to a sustained increase in Vaquita. The scenario involving the second-largest closure, covering the 2008 Vaquita distribution, would be the best compromise between conservation and fishery catch. Mature Vaquita numbers would increase two-fold while fisheries net value would decrease moderately.	Using an ecosystem model, this study provides the first concurrent analysis of the potential effects of management actions on both Vaquita and the Upper Gulf fisheries.	Model does not fully capture statistical uncertainty in all parameters. Intended for strategic evaluations of policy options rather than explicitly setting gear or catch restrictions. Several assumptions concerning predator-prey ecology and age-specific bycatch rates are made.
32	*Spatial & temporal closures*	Niemi *et al.* 2013	Lake Saimaa, Finland	Various	Various	Saimaa ringed seal (*Phoca hispida saimensis*)	Two fishing restrictions have so far been established: a seasonal closure and year-round ban of some gear types. Current seasonal closures cover 63% of the estimated seal distribution. Gear restrictions are in place throughout 55% of their distribution. Recommends this be increased to cover the entire range due to high risk of extinction. Temporal coverage of current seasonal restrictions is not adequate, with over 50% of entangled seals bycaught outside of these closures. To meet the short-term goal of at least 400 living seals by 2025, this closure needs to be reviewed and made more comprehensive.	First quantitative assessment of Saimaa ringed seal distribution and home range using GPS and VHF tags. Aims to study their movements to improve the effectiveness of conservation efforts. Small number of tracked animals (9 adults, 11 pups), tagged over the course of several years for periods ranging from 55 to 306 days.	Different tracking methods used for pups and adults, which could lead to data bias. The less intensive VHF monitoring may miss significant animal movements, resulting in a smaller estimate of home range than the corresponding GPS estimate.
33	*Various*	Rojas-Bracho & Reeves 2013	Gulf of California , Mexico	Gill net	Shrimp, Finfish	Vaquita (*Phocoena sinus*)	The first Vaquita refuge proved to be ineffective in reducing bycatch. Reasons for this include: protection for only half the population at any one time; delays in introducing alternative options to fishers; lack of enforcement; disjointed and complex closure rules. The latest closures likely slowed the vaquita's decline, though the goal of eliminating gillnet use by 2012 was not reached. Reasons for this failure include: poor fishery management and lack of knowledge about fishing effort; voluntary nature	Reviews and evaluates the mitigation techniques used to protect Vaquita from bycatch in recent years (2005 onwards).	

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							of mitigation measures; lack of enforcement; slow research on alternative fishing methods. A trawl has been tested that could safely replace gillnets for the shrimp fishery. Similar alternatives urgently need to be developed for finfish.		
34	*Various*	Orphanides & Palka 2013	Northwest Atlantic	Demersal gill net	Various	Harbour porpoise (*Phocoena phocoena*)	Bycatch decreased initially but then increased to unacceptable levels during the middle years before becoming moderate. Though it fluctuated, it was not reduced sufficiently to maintain the mean annual mortality below potential biological removal (PBR) levels. Changes in fishing effort and distribution played a large role in bycatch changes, as did poor enforcement and compliance. Compliance levels had an inverse relationship with bycatch levels. Pingers appear to have not been as effective in the operational fisheries as they were during scientific experiments.	Reviews the results of the Harbour Porpoise Take Reduction Plan from 1999 to 2010, which includes a mixture of time-area closures, pingers and other gear modifications. Examines trends in bycatch, compliance and changes in fisheries involved. Bycatch was observed for a small, but representative sample of trips (roughly 4% of all trips annually).	Early pinger models were reported to have a high failure rate. Observers did not have a reliable way to test whether they were working.
35	*Various*	Read 2013	Gulf of Maine, New England, USA	Demersal gill net	Various	Harbour porpoise (*Phocoena phocoena*)	Implementation of these measures reduced annual bycatch from a high of 2900 in 1990 to 323 in 1999, the first year in which bycatch dropped below the PBR level. The clear PBR goal attributed to this success. Monitoring programs both before and after implementation were very important in spurring management action and evaluating effectiveness.	Reviews the development of conservation strategies to address bycatch of harbour porpoise from 1990 to 1999. Combines time-area closures and the use of acoustic alarms.	