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REVIEWS

Technical mitigation to reduce marine mammal bycatch and entanglement in commercial fishing gear: lessons learnt and future directions

Sheryl Hamilton · G. Barry Baker

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Abstract Fisheries bycatch is one of the biggest threats to marine mammal populations. A literature review was undertaken to provide a comprehensive assessment and synopsis of gear modifications and technical devices to reduce marine mammal bycatch in commercial trawl, purse seine, longline, gillnet and pot/trap fisheries. Successfully implemented mitigation measures include acoustic deterrent devices (pingers) which reduced the bycatch of some small cetacean species in gillnets, appropriately designed exclusion devices which reduced pinniped bycatch in some trawl fisheries, and various pot/trap guard designs that reduced marine mammal entrapment. However, substantial development and research of mitigation options is required to address the bycatch of a range of species in many fisheries. No reliably effective technical solutions to reduce small cetacean bycatch in trawl nets are available, although loud pingers have shown potential. There are currently no technical options that effectively reduce marine mammal interactions in longline fisheries, although development of catch and hook protection devices is promising. Solutions are also needed for species, particularly pinnipeds and small cetaceans, that are not deterred by pingers and continue to be caught in static gillnets. Large whale entanglements in static gear, particularly buoy lines for pots/traps, needs urgent attention although there is encouraging research on rope-less pot/trap systems and identification of rope colours that are more detectable to whale species. Future mitigation development and deployment requires rigorous scientific testing to determine if significant bycatch reduction has been achieved, as well as consideration of potentially conflicting mitigation outcomes if multiple species are impacted by a fishery.

Keywords By-catch · Cetacean · Gillnet · Longline · Pinniped · Trawl

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Introduction

Marine mammals are incidentally killed in a range of fisheries throughout the world (Lewison et al. 2014; Read et al. 2006). This *bycatch* in active fishing gear is

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one of the biggest threats to marine mammal populations, particularly cetaceans (whales, dolphins and porpoises) and pinnipeds (e.g. seals and sea lions) (Jaiteh et al. 2013; Read 2008; Reeves et al. 2013). As these species are long-lived with high adult survival and low breeding productivity, populations are often slow to recover from declines, even under conducive environmental conditions. Therefore, anthropogenic activities that increase mortality levels, such as fisheries bycatch, can have significant, long-term population impacts (Gilman 2011; Lewison et al. 2004; Reeves et al. 2003).

Cetaceans and pinnipeds interact with fisheries as they may: (1) feed on the same target species or associated non-target species of a fishery, (2) be attracted to fishing operation discards, and/or (3) passively encounter fishing gear in the water column (Fertl and Leatherwood 1997; Hamer et al. 2012). These interactions may result in the bycatch of individuals caught in active fishing components (e.g. nets, hooks, traps), or entangled in supporting gear and lines. Bycatch in trawl, purse seine, longline, gillnet and pot/trap fisheries has been identified as a major threat to many species (Hall 1998; Hamer et al. 2012; Hamer and Goldsworthy 2006; Hamer et al. 2008; Knowlton et al. 2012; Reeves et al. 2013; Werner et al. 2015). Other gear types, such as those used in troll and squid jigging fisheries, are considered to be more selective in targeting species and, therefore, have less bycatch risk (Wakefield et al. 2017).

Over the past decade, there has been heightened awareness and attention on the development of solutions to reduce fisheries bycatch. For example, the Food and Agriculture Organization of the United Nations (FAO), as part of an ongoing commitment to bycatch management work, convened a workshop to consider means to reduce marine mammal mortality in fisheries and aquaculture operations (FAO 2018). Also, a number of bycatch mitigation reviews have focussed on particular aspects of mitigation or gear type, or on certain species or species groups (Dawson et al. 2013; Geijer and Read 2013; Hamer et al. 2012; How et al. 2015; Laverick et al. 2017; Leaper and Calderan 2018; Werner et al. 2006, 2015). However, there is no readily accessible synthesis of best practice mitigation methods for marine mammals and, furthermore, the high level of bycatch that continues to occur in fisheries around the world (Gray and Kennelly 2018; Reeves et al. 2013) necessitates an update and expansion from previously published assessments. This paper presents the first comprehensive global review of technical mitigation measures designed to reduce marine mammal bycatch in commercial fishing gear, including assessments of mitigation testing, effectiveness and, where relevant, operational deployment, and a synthesis of best practice mitigation and areas requiring greater attention.

Methods and scope

Although there has been considerable progress in some fisheries regarding the development, testing and implementation of mitigation measures to reduce marine mammal bycatch in commercial fishing gear, much of this information is not easily accessible. A literature review was undertaken using a range of sources including peer-reviewed journals, unpublished reports, magazine articles, conference papers, websites, and information from government and non-government organisations. An electronic literature search was conducted up to and including August 2018 using Web of Science and Google Scholar. Search terms were *bycatch*, *by-catch* and/or *mitigat** combined with: *fisher**, *trawl*, *purse seine*, *longline*, *gillnet*, *pot*, *trap*, *line*, *cetacean*, *whale*, *dolphin*, *porpoise*, *pinniped*, *seal*, *sea lion* in any field. References from other published papers and the authors' personal bibliographic resources were used to identify relevant papers. Key researchers were contacted via email or ResearchGate (https://www.researchgate.net/) to access relevant non-published reports.

Studies on the development and implementation of technical mitigation measures (i.e. gear modifications and mitigation devices) for marine mammal bycatch in commercial trawl, purse seine, longline, gillnet and pot/trap fishing gear were reviewed. Fisheries not considered to be high risk to marine mammal species, such as trolling and jigging (Arnould et al. 2003), and mitigation of mortalities from lost, discarded or abandoned gear (i.e. ghost fishing) were not included. Reviewed studies predominantly addressed cetacean and/or pinniped bycatch as most mitigation research has focussed on these taxa.

Technical measures are presented on a fishing gear basis (trawl, purse seine, longline, gillnet and pot/trap) with the exception of *pingers* and a range of *weakened gear*, which are applicable to different fishing gears and are therefore more effectively dealt with in a collated section. For each measure, the scientific evidence for mitigation effectiveness, caveats or uncertainties in the methods or results, research requirements and, where possible, recommendations for effective operational implementation were identified.

Although outside the scope of this review, it was apparent that effective bycatch mitigation strategies often comprise a suite of management measures in conjunction with technical mitigation. These include traditional input and output controls, operational adjustments through 'codes of practice' protocols (e.g. 'move-on' provisions, handling and release protocols) and implementation of appropriately designated spatial and/or temporal closures (Hamer and Goldsworthy 2006; Hamer et al. 2008, 2011; Read 2013; Reyes et al. 2012; Rojas-Bracho and Reeves 2013; Slooten 2013; Tixier et al. 2014; Werner et al. 2015). Instigation of multi-jurisdictional agreements, regulations and/or legislation to facilitate mitigation implementation are also likely to be important (Geijer and Read 2013; Leaper and Calderan 2018).

Results of reviewed technical mitigation measures

A synopsis of the technical mitigation assessment is provided below, with details on mitigation and fishery-specific studies provided in Supplementary Material, Tables S1–S5. A summary of the assessment and effectiveness of each technical measure identified is provided in Table 1. Where appropriate, a subjective evaluation of the economic viability, practicality, impact on target catch and the ease of compliance monitoring for each technical measure is provided in Table 2. However, although this provides a general overview, due to fishery-specific characteristics (e.g. size of target species, operational elements), the evaluation responses are not definitive, and results may differ across fisheries. For example, a range of fishery-specific factors would affect the economic feasibility of mitigation implementation such as operational specifications, target species value and how much the mitigation reduces target species damage or depredation by bycatch species.

Mitigation relevant to multiple types of fishing gear

Pingers (Acoustic deterrent devices)

Pingers, small electronic devices with relatively low acoustic outputs (< 160 dB), were developed to reduce high levels of small cetacean bycatch in gillnets (Dawson et al. 2013; Kraus et al. 1997; Reeves et al. 2013). Pingers also include louder devices (> 132 dB) to deter marine mammals from trawl nets or to reduce pinniped or odontocete interactions and depredation around aquaculture, longline or pot/trap operations (Dawson et al. 2013; Hamer et al. 2012; Mackay and Knuckey 2013). The effectiveness of pingers in reducing bycatch differs between trawl, longline, gillnet and pot/trap gear (Table 1), and between species and fisheries. Furthermore, the economic viability of deploying pingers varies between gear types. It is likely to be more economically viable to deploy pingers on gear contained within a relatively small range (e.g. gillnets, trawls, pot/trap lines) than using pingers to deter marine mammals from longlines, which can extend over tens of kilometres (Table 2).

For trawl fisheries (Table S1), while there are likely to be inter- and intra-specific differences in responses to pingers with different signals, the effectiveness of pingers in reducing cetacean bycatch is unclear. Correctly deployed, loud pingers (e.g. *Dolphin Dissuasive Devices*®, '*DDD*') may reduce common dolphin (*Delphinus delphis*) bycatch in seabass (*Dicentrarchus labrax*) pair trawl fisheries (Northridge et al. 2011), although decreases in reported bycatch may be partly due to reduced fishing effort (de Boer et al. 2012) and results from other trials (with different pinger models) were inconclusive (Morizur et al. 2008). Furthermore, controlled experiments in the absence of the loud operational conditions of trawls indicated pingers may not provide a consistently effective deterrent for common dolphins (Berrow et al. 2009). Pingers may also have less effect on foraging compared to travelling groups of cetaceans (van Marlen 2007). Neither DDDs nor quieter pingers were effective in reducing bottlenose dolphin (*Tursiops truncatus*) interactions in Australia's Pilbara demersal fish trawl fishery (Santana-Garcon et al. 2018; Stephenson and Wells 2006). While one study suggested pingers may increase rates of bottlenose

Table 1 Summary of whether a technical measure developed to reduce pinniped and/or cetacean bycatch in commercial trawl, purse seine, longline, gillnet and pot/trap operations has been *assessed* (*A*) and if there is evidence that it is *effective* (*E*) in reducing bycatch

Technical measure	Trawl				Purse seine				Longline			
	Pinniped		Cetacean		Pinniped		Cetacean		Pinniped		Cetacean	
	A	E	A	E	A	E	A	E	A	E	A	E
Acoustic deterrent devices (pingers)	No	?	Yes	?	–	–	–	–	No	?	Yes	No
Acoustic scarers; e.g. alarm or predator calls, explosions	–	–	–	–	?	No	Yes	No	No	?	Yes	No
Acoustically reflective nets	–	–	–	–	–	–	–	–	–	–	–	–
Auto-trawl systems	No	?	No	?	–	–	–	–	–	–	–	–
Back-down manoeuvre with Medina panels	–	–	–	–	No	?	Yes	Yes	–	–	–	–
"Buoyless" nets	–	–	–	–	–	–	–	–	–	–	–	–
Catch protection devices—demersal longline	–	–	–	–	–	–	–	–	No	?	Yes	?
Catch protection devices (triggered)—pelagic longline	–	–	–	–	–	–	–	–	No	?	Yes	?
"Dolphin gate" with additional weights	–	–	–	–	No	?	Yes	?	–	–	–	–
Exclusion device: hard grid and top-opening escape	Yes	Yes	Yes	No	–	–	–	–	–	–	–	–
Exclusion device: soft/flexible grid and top-opening escape	Yes	?	Yes	No	–	–	–	–	–	–	–	–
Exclusion device: hard grid and bottom-opening escape	Yes	?	Yes	?	–	–	–	–	–	–	–	–
Exclusion device: soft/flexible grid and bottom-opening escape	No	?	Yes	No	–	–	–	–	–	–	–	–
Mesh enlargement	–	–	–	–	No	No	?	No	–	–	–	–
Net binding	No	?	No	?	–	–	–	–	–	–	–	–
Net colour	No	?	No	?	–	–	–	–	–	–	–	–
Passive acoustic deterrents	–	–	–	–	–	–	–	–	No	?	Yes	?
Pot/trap excluder devices	–	–	–	–	–	–	–	–	–	–	–	–
Reduced strength rope	–	–	–	–	–	–	–	–	–	–	–	–
Reduced strength nets	–	–	–	–	–	–	–	–	–	–	–	–
Rope colour changes	–	–	–	–	–	–	–	–	–	–	–	–
Rope or mesh barriers	No	?	Yes	?	–	–	–	–	–	–	–	–
Rope-less pot/trap systems	–	–	–	–	–	–	–	–	–	–	–	–
"Seal socks"	–	–	–	–	–	–	–	–	–	–	–	–
Sinking groundlines	–	–	–	–	–	–	–	–	–	–	–	–
Stiff ropes	–	–	–	–	–	–	–	–	–	–	–	–
Visually detectable nets	–	–	–	–	–	–	–	–	–	–	–	–
Weak hooks	–	–	–	–	–	–	–	–	No	?	Yes	?
Weak links	–	–	–	–	–	–	–	–	–	–	–	–

Table 1 continued

Technical measure	Gillnet				Pot/trap			
	Pinniped		Cetacean		Pinniped		Cetacean	
	A	E	A	E	A	E	A	E
Acoustic deterrent devices (pingers)	No	?	Yes	Yes	No	?	Yes	?
Acoustic scarers; e.g. alarm or predator calls, explosions	–	–	–	–	–	–	–	–
Acoustically reflective nets	No	?	Yes	No	–	–	–	–
Auto-trawl systems	–	–	–	–	–	–	–	–
Back-down manoeuvre with Medina panels	–	–	–	–	–	–	–	–
"Buoyless" nets	No	?	No	?	–	–	–	–
Catch protection devices—demersal longline	–	–	–	–	–	–	–	–
Catch protection devices (triggered)—pelagic longline	–	–	–	–	–	–	–	–
"Dolphin gate" with additional weights	–	–	–	–	–	–	–	–
Exclusion device: hard grid and top-opening escape	–	–	–	–	–	–	–	–
Exclusion device: soft/flexible grid and top-opening escape	–	–	–	–	–	–	–	–
Exclusion device: hard grid and bottom-opening escape	–	–	–	–	–	–	–	–
Exclusion device: soft/flexible grid and bottom-opening escape	–	–	–	–	–	–	–	–
Mesh enlargement	–	–	–	–	–	–	–	–
Net binding	–	–	–	–	–	–	–	–
Net colour	–	–	–	–	–	–	–	–
Passive acoustic deterrents	–	–	–	–	–	–	–	–
Pot/trap excluder devices	–	–	–	–	Yes	Yes	Yes	Yes
Reduced strength rope	–	–	–	–	No	?	No	?
Reduced strength nets	Yes	?	No	?	–	–	–	–
Rope colour changes	–	–	–	–	–	–	Yes	?
Rope or mesh barriers	–	–	–	–	–	–	–	–
Rope-less pot/trap systems	–	–	–	–	–	–	Yes	?
"Seal socks"	–	–	–	–	Yes	Yes	No	?
Sinking groundlines	–	–	–	–	–	–	Yes	No
Stiff ropes	–	–	–	–	–	–	Yes	No
Visually detectable nets	No	?	No	?	–	–	–	–
Weak hooks	–	–	–	–	–	–	–	–
Weak links	No	?	No	?	No	?	Yes	?

"?" for *assessed* category = unclear whether there has been any assessment of the measure

"?" for *effective* category = lack of knowledge of the measure's effectiveness, results have been inconclusive and/or more trials are needed

"–" = measure is not applicable for relevant fishing gear

Table 2 Subjective evaluation of the economic viability (EV), practicality (P), impact on target catch (ITC) and compliance requirement (CR) for mitigation measures shown to be, or have the potential to be, effective in reducing pinniped and/or cetacean bycatch in trawl, purse seine, longline, gillnet and pot and trap fishing gear. Note that, although this evaluation provides a general overview, due to fishery-specific characteristics (e.g. size of target species, operational elements), responses may differ across fisheries

Technical measure	Trawl				Purse seine				Longline			
	EV	P	ITC	CR	EV	P	ITC	CR	EV	P	ITC	CR
Acoustic Deterrent Devices (Pingers)	Yes	Maybe	No	OBS	–	–	–	–	No	No	Unk	OBS
Acoustic scarers; e.g. alarm or predator calls, explosions	–	–	–	–	–	–	–	–	Maybe	Maybe	Unk	OBS
Acoustically reflective nets	–	–	–	–	–	–	–	–	–	–	–	–
Auto-trawl systems	Yes	Yes	No	OBS	–	–	–	–	–	–	–	–
Back-down manoeuvre with Medina panels	–	–	–	–	Yes	Yes	No	OBS	–	–	–	–
“Buoyless” nets	–	–	–	–	–	–	–	–	–	–	–	–
Catch protection devices—demersal longline	–	–	–	–	–	–	–	–	Yes	Maybe	No	OBS
Catch protection devices (triggered)—pelagic longline	–	–	–	–	–	–	–	–	Yes	Maybe	No	OBS
“Dolphin gate” with additional weights	–	–	–	–	Yes	Maybe	No	OBS	–	–	–	–
Exclusion device: hard grid and top-opening escape	Yes	Maybe	Maybe	OBS	–	–	–	–	–	–	–	–
Exclusion device: soft/flexible grid and top-opening escape	Yes	Maybe	Maybe	OBS	–	–	–	–	–	–	–	–
Exclusion device: hard grid and bottom-opening escape	Yes	Maybe	Maybe	OBS	–	–	–	–	–	–	–	–
Exclusion device: soft/flexible grid and bottom-opening escape	Yes	Maybe	Maybe	OBS	–	–	–	–	–	–	–	–
Net binding	Yes	Yes	No	OBS	–	–	–	–	–	–	–	–
Net colour	Maybe	Yes	No	DCK[§]	–	–	–	–	–	–	–	–
Passive acoustic deterrents	–	–	–	–	–	–	–	–	Yes	Maybe	No	OBS
Pot/trap excluder devices	–	–	–	–	–	–	–	–	–	–	–	–
Reduced strength rope	–	–	–	–	–	–	–	–	–	–	–	–
Reduced strength nets	–	–	–	–	–	–	–	–	–	–	–	–
Rope colour changes	–	–	–	–	–	–	–	–	–	–	–	–
Rope or mesh barriers	Yes	Maybe	Maybe	OBS	–	–	–	–	–	–	–	–
Rope-less pot/trap systems	–	–	–	–	–	–	–	–	–	–	–	–
“Seal socks”	–	–	–	–	–	–	–	–	–	–	–	–
Visually detectable nets	–	–	–	–	–	–	–	–	–	–	–	–
Weak hooks	–	–	–	–	–	–	–	–	Maybe	Maybe	No	DCK
Weak links	–	–	–	–	–	–	–	–	–	–	–	–

Table 2 continued

Technical measure	Gillnet				Pot/trap			
	EV	P	ITC	CR	EV	P	ITC	CR
Acoustic deterrent devices (pingers)	Yes	Yes	No	OBS	Yes	Yes	No	OBS
Acoustic scarers; e.g. alarm or predator calls, explosions	–	–	–	–	–	–	–	–
Acoustically reflective nets	Maybe	Yes	No	DCK*	–	–	–	–
Auto-trawl systems	–	–			–	–	–	–
Back-down manoeuvre with Medina panels	–	–	–	–	–	–	–	–
"Buoyless" nets	Yes	Maybe	Maybe	OBS	–	–	–	–
Catch protection devices—demersal longline	–	–	–	–	–	–	–	–
Catch protection devices (triggered)—pelagic longline	–	–	–	–	–	–	–	–
"Dolphin gate" with additional weights	–	–	–	–	–	–	–	–
Exclusion device: hard grid and top-opening escape	–	–	–	–	–	–	–	–
Exclusion device: soft/flexible grid and top-opening escape	–	–	–	–	–	–	–	–
Exclusion device: hard grid and bottom-opening escape	–	–	–	–	–	–	–	–
Exclusion device: soft/flexible grid and bottom-opening escape	–	–	–	–	–	–	–	–
Net binding	–	–	–	–	–	–	–	–
Net colour	–	–	–	–	–	–	–	–
Passive acoustic deterrents	–	–	–	–	–	–	–	–
Pot/trap excluder devices	–	–	–	–	Yes	Yes	Maybe	OBS
Reduced strength rope	–	–	–	–	Yes	Yes	No	DCK
Reduced strength nets	Yes	Yes	Unk	DCK	–	–	–	–
Rope colour changes	–	–	–	–	Yes	Yes	No	DCK
Rope or mesh barriers	–	–	–	–	–	–	–	–
Rope-less pot/trap systems	–	–	–	–	Yes	Maybe	No	DCK
"Seal socks"	–	–	–	–	Yes	Yes	Unk	OBS
Visually detectable nets	Yes	Yes	Maybe	DCK	–	–	–	–
Weak hooks	–	–	–	–	–	–	–	–
Weak links	Yes	Yes	Unk	OBS	Yes	Yes	No	OBS

Economically viable (EV): based on the cost for initial outlay plus any ongoing maintenance = *yes*, *no*, *maybe*

Practicality (P): i.e. has no great impact on fishing operation and operational efficiency = *yes*, *no*, *maybe*

Impact target catch (ITC): i.e. could cause a reduction in the amount or quality of catch = *yes*, *no*, *maybe*, *unk* (= *unknown*)

Compliance requirement (CR): either requiring at-sea observations (*OBS*) or whether dockside inspections would be adequate (*DCK*)

"—" = measure is not applicable for relevant fishing gear or assessed to be ineffective for pinnipeds and cetaceans in that type of gear (see Table 1)

*Only if all nets on board were of appropriate material. A mix of netting material would require 'OBS'

§Only if all trawl nets on board were of appropriate colour and Risso's (*Grampus griseus*) dolphin bycatch in mid-Atlantic bottom trawl fisheries, there is low confidence in this finding due to small sample sizes and limited information on the type and quantity of deployed pingers (Lyssikatos 2015).

In longline fisheries (Table S3), while there has been a high degree of variability in device design and deployment, there is no clear evidence that pingers effectively deter marine mammals (Hamer et al. 2012; Tixier et al. 2015; Werner et al. 2015). This may be largely due to the difficulty in protecting longlines which are set over large distances (Rabearisoa et al. 2012).

In gillnet fisheries (Table S4), although pingers have effectively reduced the bycatch of some small cetacean species, the results are not universal and mitigation effectiveness is likely to be species- and fishery-specific. A number of studies have shown that pingers reduced harbour porpoise (*Phocoena phocoena*) bycatch (Dawson et al. 2013; Kraus et al. 1997; Larsen and Eigaard 2014; Larsen et al. 2013; Palka et al. 2008; Reeves et al. 2013). However, results for bottlenose dolphins have been less clear with some research reporting significantly reduced interactions (Crosby et al. 2013; Gazo et al. 2008; Leeney et al. 2007; Mangel et al. 2013), while others showed no deterrent effect (Cox et al. 2003; Erbe et al. 2016). Pingers have been ineffective, or the results have been inconclusive, in deterring Hector's dolphin (*Cephalorhynchus hectori*), tucuxi (*Sotalia fluviatilis*), and other small coastal species such as the Australian snubfin (*Orcaella heinsohni*) and humpback dolphin (*Sousa chinensis*) (Berg Soto et al. 2013; Dawson and Lusseau 2005; Dawson and Slooten 2005). Pingers may also attract some species, particularly pinnipeds, to depredate captured fish (Bordino et al. 2002; Mackay and Knuckey 2013). Although initial testing showed California sea lion (*Zalophus californianus*) and northern elephant seal (*Mirounga angustirostris*) bycatch reduced with pinger use (Barlow and Cameron 2003), monitoring of pinger deployment over 14 years subsequently showed sets with pingers had almost twice the amount of California sea lion bycatch although this increase was most likely due to increased sea lion abundance and was not considered to be caused by pinger use (Carretta and Barlow 2011). There is no indication pingers would reduce bycatch risk for other species of seal, sea lion or dugong (*Dugong dugon*) in gillnets (Bordino et al. 2002; Gearin et al. 2000; Hodgson et al. 2007; Northridge et al. 2011). As pingers might deter some cetaceans while attracting some pinnipeds, addressing a bycatch issue is likely to be challenging if more than one species is at risk and they have conflicting responses to pingers (Mackay and Knuckey 2013).

For pot/trap fisheries (Table S5), pinger effectiveness in deterring large whales from high-risk entanglement areas, particularly pot or trap fishery operations, appears to be variable depending on species, migration direction and social category. In Canadian inshore trap fisheries, acoustic devices appeared to reduce the collision frequency between humpback whales (*Megaptera novaeangliae*) and cod traps (Lien et al. 1992). However, in Australia, while southward migrating humpback whales exhibited aversion behaviour to acoustic stimuli (Dunlop et al. 2013), northward migrating whales showed no detectable response to pingers (Harcourt et al. 2014; Pirotta et al. 2016). There were indications that pingers could potentially deter grey whales (*Eschrichtius robustus*) from high risk coastal areas, although results were inconclusive due to low statistical power (Lagerquist et al. 2012).

Ensuring pingers are functioning correctly and with the required number in the correct net location is important for maintaining effectiveness in gillnet fisheries (Orphanides and Palka 2013). However, the financial cost of implementing pingers may limit their applicability in many developing countries and/or smaller fisheries (Dawson et al. 1998, 2013; Read 2008), and more cost-effective, durable pingers are needed (Crosby et al. 2013). Pingers are also unlikely to be effective in deterring dolphins if they are not fully functional (e.g. fully charged batteries) or in suboptimal locations on trawl gear (Deepwater Group 2018; Northridge et al. 2011), and they should be positioned to ensure they do not impact operational equipment, such as net monitoring systems (Morizur et al. 2007).

Evidence of harbour porpoise habituation to pingers, which would reduce their effectiveness in mitigating gillnet bycatch, was provided by some experimental studies (Carlstrom et al. 2009; Cox et al. 2001; Dawson et al. 2013; Gearin et al. 2000; Read 2013), but not others (Hardy et al. 2012). However, long-term studies monitoring operational gillnets showed no sign of harbour porpoise, common dolphin or beaked whale habituation to pingers (Carretta and

Barlow 2011; Dawson et al. 2013; Palka et al. 2008). Inshore, resident porpoise populations may be more likely to develop habituation to pingers than more migratory species (Dawson et al. 1998, 2013). The effectiveness of pingers in deterring coastal, inshore or river finless porpoises (*Neophocaena* spp.) from gillnets decreased after a few months, and developing regimes which include periods with no pinger use (Amano et al. 2017), as well as randomising pinger frequency, time interval and strength, may help to maintain effectiveness. Developing 'responsive pingers' for gillnets, which only emit sounds in response to cetacean echolocations, may reduce the likelihood of pinger habituation for some species (Leeney et al. 2007; Waples et al. 2013). Bottlenose dolphins may become *more* sensitised to pingers, which could increase the mitigation effect on this species over time (Cox et al. 2003). With respect to trawl gear, some captive pinniped species became habituated to pingers on a simulated net and continued to depredate netted fish, while some dolphin species charged the netting despite pinger presence (Bowles and Anderson 2012). An interactive pinger for pelagic trawls, designed to emit signals in response to the presence of dolphin echolocations, may delay habituation and reduce noise pollution in the marine environment, with initial tests showing evasive behavioural responses from bottlenose dolphins, although not from common dolphins (van Marlen 2007). In longline operations, there is evidence that false killer whales (*Pseudorca crassidens*) and killer whales (*Orcinus orca*) became habituated to acoustic devices (Mooney et al. 2009; Tixier et al. 2015).

The increasing level of anthropogenic sound in the marine environment may negatively impact the behaviour, physiology and auditory systems of some marine species (Kastelein et al. 2015), with indications that some gillnet pingers may affect target and non-target fish (Goetz et al. 2015; Kastelein et al. 2007). Pinger deployment could impact small cetacean species that are neophobic and with small, restricted ranges by excluding them from crucial habitat, with the displacement effect potentially more pronounced in coastal locations where topographical features limit access to key bodies of water (Dawson et al. 2013). In longline operations, there is concern that frequent exposure to higher amplitude devices may affect the echolocation ability of killer whales (Tixier et al. 2015).

Weakened gear

Different types of weakened gear, designed to release caught animals, have been proposed and/or trialled in different fisheries (Table 1) including:

a. *"Weak" hooks* in longline fisheries (Table S3): These may reduce the bycatch risk for some species (e.g. false killer whales) without loss of target catch (Bayse and Kerstetter 2010; Bigelow et al. 2012; McLellan et al. 2015; Werner et al. 2015), although there is currently insufficient evidence to support this. Low rates of cetacean interactions during experimental trials has hampered the ability to assess bycatch reduction (Bigelow et al. 2012). Weak hooks would not reduce interactions or prevent depredation (Hamer et al. 2015; Werner et al. 2015).
b. *Reduced-strength nets or ropes*: Thin twine gillnets may significantly reduce seal and harbour porpoise bycatch compared to thick twine nets (Northridge et al. 2003) (Table S4). Similarly, as strong polypropylene ropes used in modern pot/-trap fisheries have increased the mortality risk of entangled cetaceans, use of ropes with reduced breaking strengths could substantially decrease mortalities of whales entangled in fixed gear (Knowlton et al. 2016) (Table S5).
c. *Weak links* between the vertical line from a pot/trap to a buoy: These do not appear to have reduced the incidence or severity of whale entanglements in USA lobster fisheries (Knowlton et al. 2012, 2016; Pace et al. 2014; Salvador et al. 2008; Van der Hoop et al. 2013) (Table S5). Also, when buoys separate from vertical pot or trap lines, released whales may retain sections of gear (Laverick et al. 2017; Moore 2009). Some USA fisheries require weak links in gillnets to allow entangled whales to break free (NOAA 2018), although no research was identified that tested the efficacy of this measure (Table S4).

Trawl

Marine mammals are frequently caught in pelagic or midwater trawls as these often target the same pelagic species eaten by marine mammals, have relatively high tow speeds with large nets, and usually operate within marine mammal diving ranges for extended periods (Fertl and Leatherwood 1997; Hall et al. 2000) (Table S1). However, in US fisheries, marine mammals are caught more often in demersal rather than midwater trawls (Carretta et al. 2017; Jannot et al. 2011; Waring et al. 2016). The technical mitigation measures identified and assessed for trawls, in addition to pingers (see "Pingers (Acoustic Deterrent Devices)" section), are *net colour, net binding*, *exclusion devices*, *rope or mesh barriers* and *auto-trawl systems* (Table 1, Table S1).

Net colour

In an Australian fishery, more bottlenose dolphins were caught in a grey trawl net compared to a standard green net, although management variations between the two trial vessels, resulting in different net speeds through the water during winching, could also have contributed to bycatch differences (Stephenson and Wells 2006). Changing net colour has not been tested as a means of reducing marine mammal bycatch risk. However, this may not be a feasible mitigation option as, particularly for some small cetacean and fur seal species that are known to deliberately enter nets to depredate the captured fish (Fertl and Leatherwood 1997; Hamer and Goldsworthy 2006; Lyle et al. 2016; Wakefield et al. 2017), bycatch risk may not be linked to their lack of awareness of a trawl net's presence. Visual detection of nets may also be limited if visibility is poor or variable at fishing depths. Furthermore, as well as vision, many cetacean species may primarily rely on echolocation to forage and pinnipeds may use tactile senses (Martin and Crawford 2015).

Net binding

An organic material, such as sisal string, is used to bind the net until it has sunk below the water surface. Once the trawl doors are paid away, the water force separating the doors breaks the bindings so the net can form its standard operational position. Net binding, used to mitigate seabird bycatch during net shots (Sullivan et al. 2004), has also been used in some Australian fisheries to reduce fur seal (*Arctocephalus* spp.) interactions during setting (Australian Fisheries Management Authority, personal communication), although there is a lack of operational information or testing to determine whether this effectively reduces seal bycatch. As marine mammal interactions often occur during the haul (Hamer and Goldsworthy 2006), net binding, if it is shown to be effective, may need to be used in combination with other mitigation.

Exclusion devices with separation grids

It is widely accepted that appropriately designed exclusion devices successfully prevent mortalities of a range of non-target marine species in nets without significantly impacting target catch (Dotson et al. 2010; Griffiths et al. 2006; Hamilton and Baker 2015a; Wakefield et al. 2017; Zeeberg et al. 2006), although there are differing outcomes for pinnipeds and cetaceans. The grid design and escape hole configuration of exclusion devices need to ensure target species flow smoothly into the codend without compromising catch quality and quantity (Table 2), while ensuring all size classes of the non-target marine mammal species are prevented from passing into the codend and can escape (Hamilton and Baker 2015a). In fisheries with large target species, designing grids that have no impact on target catch is likely to be more challenging.

Top-opening, hard-grid exclusion devices (Figure S1) have effectively reduced pinniped bycatch in a number of trawl fisheries (CCAMLR 2017; Hamilton and Baker 2015a; Lyle et al. 2016; Tilzey et al. 2006). Operational constraints may influence exclusion device design, which could limit bycatch reduction. For example, on-board net drum storage may necessitate top-opening devices to have flexible grids, as an upwardly angled grid is counter to net drum rotation. However, soft-grids deformed under a seal's weight causing partial entanglements, provided no passive assistance in directing seals out an opening, and flexible grid distortion may also restrict the flow of target species into the codend resulting in reduced catches (Bord Iascaigh Mhara and University of St Andrews 2010; Lyle et al. 2016) (Table 2).

There has been limited success in demonstrating exclusion devices effectively reduce cetacean bycatch. Dolphins may deliberately enter trawl nets to depredate captured fish but do not appear to manoeuvre as easily as pinnipeds within the confines of a net (Jaiteh et al. 2013; Lyle et al. 2016). They appear to become distressed when far into nets and unable to find, or negotiate escapes, particularly those with bottom-opening exits (Jaiteh et al. 2014; Wakefield et al. 2017;

Zeeberg et al. 2006). While there are reports of bottlenose dolphins seeming to favour an exit out the bottom of a net (Zollett and Rosenberg 2005), they have also been reported to preferentially attempt escape via the net mouth rather than exclusion devices and, therefore, may be more likely to die if progressing too far into a net (Wakefield et al. 2017). Exclusion devices showed potential in reducing common dolphin bycatch in UK midwater pair trawls (Northridge et al. 2011), although only a small number successfully exited via the escape hole with most appearing to detect the grid some distance beforehand and attempting to, unsuccessfully, escape in that area (Bord Iascaigh Mhara and University of St Andrews 2010). While ensuring no impact on target catch, net drag or operational functioning, it was thought that positioning exclusion devices as far forward as practical, with multiple, obvious escape routes, may be critical for small cetacean survival (van Marlen 2007).

Unobservable and unreported *cryptic* mortality may occur with exclusion devices due to injuries incurred during interactions with devices or because dead animals may fall out escape openings, although scientific evidence has shown that cryptic mortalities from direct interactions with top-opening, hard-grid exclusion devices are unlikely (Hamilton and Baker 2015a, b). A forward-facing hood, held in place with a ‘kite’ (i.e. material strip) and floats over a top-opening escape (Figure S1), directs water flow into the net across the grid and is likely to minimise potential loss of dead or incapacitated animals and target catch, while keeping the escape hole open and assisting live animals to escape (Hamilton and Baker 2015a). Target species, dead seals and dead dolphins have been observed falling out of devices with *bottom-opening* escapes, or top-opening escapes *without a cover or hood* (Hamilton and Baker 2015a; Jaiteh et al. 2014; Lyle et al. 2016; Stephenson and Wells 2006), although unaccounted mortality was considered negligible even with bottom-opening devices (Wakefield et al. 2014, 2017). While Lyle et al. (2016) stated that passive ejection of dead animals had been reported for top-opening devices citing Robertson (2015) and Wakefield et al. (2014), there is no evidence to support this. Robertson (2015) stated there were no data to show dead sea lions were either retained or passively ejected from openings, but made no differentiation between top-opening and bottom-opening devices and did not acknowledge that a hood or cover helps prevent passive loss of animals (see Hamilton and Baker 2015b). Wakefield et al. (2014) reported one incident where a dead dolphin fell out a device with a top-opening escape hole, although this occurred when the net rotated 180° during the haul so the hole (with no cover) was orientated downward.

Rope or mesh barriers

Restricting dolphin access into trawl nets may be the key to preventing mortality, although there has been limited success in deterring them from entering nets (Wakefield et al. 2017). A small number of dolphins escaped through a top-opening hole, covered with parallel ‘bungee’ cords, located ahead of a mesh barrier, though most barriers trialled in pair trawls (e.g. various designs in van Marlen 2007) had reduced target catch rates (Bord Iascaigh Mhara and University of St Andrews 2010; van Marlen 2007) (Table 2).

Auto-trawl systems

Intuitively, ensuring the net entrance does not collapse during any trawl phase should reduce entrapment risk and maintain the effective operation of installed exclusion devices, though the efficacy of auto-trawl systems as a bycatch mitigation measure requires verification. Use of otter-board sensors and eliminating sharp turns while trawling are thought to have reduced dolphin mortalities in trawl nets (Wakefield et al. 2017). Recent research assessing bottlenose dolphin interactions with trawls gives further support to improving and monitoring trawl gear stability as potentially the most effective mitigation strategy for reducing dolphin bycatch, while the use of acoustic deterrent devices was ineffective (Santana-Garcon et al. 2018).

Purse seine

In purse seine operations, bycatch mitigation has concentrated on reducing dolphin mortality, mainly related to eliminating the practice of setting around dolphin pods associated with target tuna species in the eastern Pacific Ocean (EPO) (Gilman 2011) (Table S2). Less commonly, sets on tuna schools associated with live whales have also occurred. Reducing cetacean bycatch has been mainly through the cessation of sets on dolphin-associated or whale-associated tuna schools (Hall and Roman 2013). There was a general lack of information on mitigation development for other purse seine fisheries although a '*dolphin gate*' (detachable cork-line section) and weights to help sink the cork-line were trialled in an Australian small pelagic fishery but require further development and testing to determine if effective (Hamer et al. 2008). In the EPO tuna fisheries, a shift to sets around 'Fish Aggregating Devices (FADs)' (i.e. artificial floating elements with relocation aids) raised new environmental concerns regarding overfishing and marine species' entanglement in FAD components (Hall and Roman 2013). Mitigation development currently focuses on improving FAD design to reduce shark and turtle entanglement (Restrepo and Dagorn 2011; Restrepo et al. 2014, 2016), while this appears less of an issue for marine mammals. In terms of technical mitigation, to reduce bycatch and increase the likelihood of dolphin escape, the use of *enlarged mesh sizes* was unsuccessful as target species and dolphins are often similar size, and *acoustic methods* to frighten dolphins out of nets (e.g. playback of alarms calls or killer whale sounds) were also ineffective (Gabriel et al. 2005). The primary mitigation that has substantially reduced dolphin mortality in tuna purse seine fisheries, without causing loss of entrapped tuna (Restrepo et al. 2016), has been the *'back-down' manoeuvre* with the addition of *'Medina' panels* as described by Hall and Roman (2013) (Table 1). Speedboats equipped with towing bridles can also help keep the net open and assist dolphin escape as well as the use of a raft inside the net to facilitate manual rescue (National Research Council 1992). While 'cryptic' impacts, including the post-escape mortality of injured dolphins and potential effects of chasing and encirclement on reproductive success, are a potential issue (Anderson 2014; Archer et al. 2004; Cramer et al. 2008; Gerrodette and Forcada 2005; Wade et al. 2007), no studies were identified that monitored the post-release survival of marine mammals.

Longline

While mitigation has primarily focussed on reducing the economic impact of marine mammal depredation of target catch in longline operations, depredation behaviour also puts them at risk of becoming hooked or entangled (Bigelow et al. 2012) (Table S3). Mitigation measures that have been unsuccessful in reducing interactions include the use of *explosives, chemical deterrents, flare guns* or *predator sounds* (Werner et al. 2006). An assessment of mitigation measures including spatial fisheries management, altered fishing strategies, and acoustic and physical techniques, concluded that terminal gear modifications had the greatest mitigation potential (Werner et al. 2015). In this updated review, along with pingers and weak hooks (see "Pingers (Acoustic Deterrent Devices)" and "Weakened gear" sections), mitigation with potential to reduce interactions with longlines are *passive acoustic deterrents* and *catch protection devices* (Table 1, Table S3).

Passive acoustic deterrents

Echolocation Disruption Devices and passive acoustic measures may affect a cetacean's ability to echolocate hooked fish (Hamer et al. 2012; O'Connell et al. 2015). While there were indications that spherical beads attached near longline hooks could reduce interactions between sperm whales (*Physeter microcephalus*) and longlines, it was inconclusive whether they were effective (O'Connell et al. 2015).

Catch protection devices: demersal longline

In demersal longline fisheries, odontocetes are more likely to access hooked fish during the haul compared to line soaking that may be at depths beyond their normal foraging range (Gilman et al. 2006; Guinet et al. 2015; Hamer et al. 2012; Soffker et al. 2015; Tixier et al. 2014). However, there may be exceptions to this such as recent evidence of interactions between southern elephant seals (*Mirounga leonina*) and a sub-Antarctic demersal longline fishery during the line soak period at depths > 1 km (van den Hoff et al. 2017). "Net sleeves", which cover hooked fish with the downward pressure of hauling, protect fish from depredation and reduce bycatch risk (Hamer et al. 2012; Moreno et al. 2008). The "cachalotera", a type of net sleeve, substantially reduced depredation by killer and sperm whales in the Chilean industrial Patagonian toothfish (*Dissostichus eleginoides*) longline fleet (Moreno et al. 2008) (Figure S2), although some killer whales have learnt how to depredate around cachaloteras (Arangio 2012). A similar system to reduce sperm whale depredation and seabird bycatch on Spanish vessels consists of "umbrella" devices fixed on branchlines, which open to extend over hooked fish, combined with stones for faster line sinking (Figure S3). While "umbrella and stones" net sleeve trials were promising, evidence for their efficacy in reducing interactions was inconclusive (Goetz et al. 2011). While there was no reduction in target catch rates with "cachaloteras" (Moreno et al. 2008), "umbrella and stones" net sleeves significantly reduced toothfish catch, which may be due to different attachment designs as "cachaloteras" slide up and down the branchline whereas the "umbrellas" are fixed (Goetz et al. 2011). In some operations, gear and vessel configurations (e.g. if hooks are close together and gear is coiled for storage) may make net sleeves impractical to use (O'Connell et al. 2015).

Triggered catch protection devices: pelagic longline

Compared to demersal longlines, pelagic longlines may be at risk of depredation during setting, soak time and hauling as marine mammals often occur across the same depths as target fish and, therefore, net sleeves that slide over the hook only during the haul have limited use (Hamer et al. 2015; Rabearisoa et al. 2015). Therefore, devices developed for pelagic longlines have mechanical triggers to release the net sleeve structure with the pressure when a fish is hooked. These include:

a. "Chain" devices and cone-like "cage" devices (Figure S4): Trials on Australian pelagic longlines showed all odontocete interactions occurred on branchlines without devices and there was negligible impact on target catch, although results were inconclusive due to small sample sizes (Hamer et al. 2015);
b. Eight strand "spider" devices and conical "sock" devices [see photographs in Rabearisoa et al. (2012)]: Trials on commercial tuna longliners off the Seychelles showed limited success in reducing odontocete depredation, although interaction rates were low during trials (Rabearisoa et al. 2012);
c. "DEPRED" device (Figure S5): Initial results were encouraging although, as trials used small delphinid interactions with a small pelagic fish fishery as a proxy for odontocete interactions with tuna and billfish fisheries, further development and testing is required (Rabearisoa et al. 2015).

During trials, some devices falsely triggered when a fish was not present, did not deploy when a fish was hooked, or became entangled in the longline gear (Hamer et al. 2015; Rabearisoa et al. 2012). While most devices provide a simple physical barrier to protect hooked fish, there has been preliminary testing of devices with metal wire incorporated in streamers to affect an odontocete's ability to echolocate hooked fish (McPherson et al. 2008).

Gillnet

There have been a number of reviews, with a range of focuses and objectives, relating to marine mammal bycatch and mitigation measures for gillnets (Dawson et al. 2013; Leaper and Calderan 2018; Mackay and Knuckey 2013; Northridge et al. 2017; Read 2008, 2013; Reeves et al. 2013; Uhlmann and Broadhurst 2015; Waugh et al. 2011). As it may be difficult for many marine mammal species to avoid gillnets, well-designed spatial and/or temporal fishery closures are likely to be important and effective mitigation options (Dawson and Slooten 2005; Hall and Mainprize 2005; Hamer et al. 2011, 2013; Read 2013; Rojas-Bracho and Reeves 2013; Slooten 2013). In this updated review, in addition to pingers, reduced strength nets and weak links (see "Pingers (Acoustic Deterrent Devices)" and "Weakened gear" sections), the potential mitigation options identified are *acoustically reflective nets*, *visually detectable nets* and *"buoyless" nets* (Table 1, Table S4).

Acoustically reflective nets

As nylon may be difficult for echolocating marine mammals to detect, nets that utilise different materials, or incorporate reflective components (e.g. metal compounds) into the net filament, have been trialled (Bordino et al. 2013; Larsen et al. 2007; Mooney et al. 2004; Trippel et al. 2003). Some studies showed a reduction in harbour porpoise bycatch with metal oxide nets (Larsen et al. 2007; Trippel et al. 2003, 2008) while others reported no reduction in harbour porpoise, franciscana or seal bycatch (Bordino et al. 2013; Mooney et al. 2004; Northridge et al. 2003). It was suggested that observed bycatch reduction may be due to net stiffness rather than acoustic reflectivity (Cox and Read 2004; Larsen et al. 2007). However, while increasing net stiffness could be a low-cost mitigation option (Northridge et al. 2017), there was no significant difference in franciscana bycatch between barium sulphate nets, nets with increased nylon twine stiffness and standard nets (Bordino et al. 2013). Furthermore, increased net stiffness decreased target catch rates in some studies (Larsen et al. 2007). Increasing a net's acoustic reflectivity would also be ineffective if a small cetacean encountered the net when it was not echolocating (Dawson 1991). There was also no evidence that passive acoustic additions (e.g. metal beaded chains) reduced cetacean bycatch (Hembree and Harwood 1987).

Visually detectable nets

Increasing the visual detectability of nets using illumination or visible panel inserts have not yet been tested as a mitigation option for marine mammals. Light-emitting diodes significantly reduced bycatch of other taxa and could potentially reduce the bycatch of small cetaceans (Mangel et al. 2018). Conversely, installing contrasting patterned panels to increase net detectability could possibly alert pinnipeds to gillnet presence which may increase catch depredation (Martin and Crawford 2015). To date, changing gillnet colour has not been tested as a measure to reduce marine mammal bycatch, although orange-coloured gillnets may be more apparent to some penguin species (Hanamseth et al. 2018).

"Buoyless" nets

Nets with reduced numbers of buoys per metre significantly reduced sea turtle bycatch probably due to a decreased vertical profile of the nets. While this gear modification could potentially reduce marine mammal bycatch (Peckham et al. 2016), this is yet to be verified.

Pot/Trap

Management of large whale entanglement has predominantly focussed on strategies to respond and release entangled whales or establish seasonal closures (Robbins et al. 2015; Van der Hoop et al. 2013), with less research on technical solutions to prevent interactions or entanglements (Table S5). Developing better species-specific knowledge of the interaction and mechanism of entanglement, particularly the parts of gear that whales mainly encounter, will aid in implementing effective mitigation (Johnson et al. 2005; Northridge et al. 2010). A number of potential techniques have been proposed but have not been considered a priority for development including ropes that glow underwater and lipid soluble ropes which dissolve if embedded in whale blubber (Werner et al. 2006). This review provides an updated assessment of entanglement mitigation based on previous reviews (Laverick et al. 2017; Leaper and Calderan 2018), as well as mitigation to reduce pinniped and small cetacean entrapment in pots and traps. In addition to pingers, reduced strength rope, weak links and line cutters (see "Pingers (Acoustic Deterrent Devices)" and "Weakened gear" sections), the mitigation identified are *pot/trap excluder devices*, *"seal socks"*, *sinking groundlines*, *rope-less pot/trap systems*, *rope colour changes* and *stiff ropes* (Table 1, Table S5).

Pot/trap excluder devices

Technical alterations or additions reduce the entrance size and/or shape of pots and traps to prevent marine mammals entering thereby reducing bycatch risk as well as catch depredation. The shape as well as the size of pot entrances is likely to be important to ensure target catch quantity and size range are not affected (Konigson et al. 2015). 'Bungee' cord guards reduced bottlenose dolphin interactions with crab pots (Noke and Odell 2002; Werner et al. 2006); wire guards and stronger netting reduced seal damage and bycatch risk in salmon trap-nets (Hemmingsson et al. 2008; Suuronen et al. 2006); and smaller crab fyke trap openings reduced sea otter (*Enhydra lutris*) bycatch without reducing target catch (Hatfield et al. 2011). 'Spike' excluder devices are mandatory in bycatch risk areas to prevent Australian sea lion pups and juveniles entering lobster pots, although testing of alternative industry-designed 150 mm diameter circular openings (which are more practical and safe to use) has shown they may also effectively exclude most pups (Campbell et al. 2008; Mackay and Goldsworthy 2017).

"Seal socks"

A cylindrical net attached to shallow water (< 2 m deep) fyke nets allowed trapped seals access to the surface to breathe and reduced ringed seal (*Phoca hispida botnica*) bycatch, although was less effective for Baltic grey seals (*Halichoerus grypus baltica*) (Oksanen et al. 2015).

Sinking groundlines

The implementation of measures in USA fixed-gear fisheries, including negatively buoyant or sinking groundlines which aim to lie closer to the ocean bottom, has not reduced serious injuries and mortality of northern right whales (*Eubalaena glacialis*) to sustainable levels (Brillant and Trippel 2010; Knowlton et al. 2012).

Rope-less pot/trap systems

To reduce cetacean entanglement risk, rope-less systems remotely release buoys linked to pots or traps, thereby reducing surface markers with vertical lines in the water column. There are no published studies that show rope-less systems mitigate bycatch or are practical and cost-effective for implementation in operational fisheries (Laverick et al. 2017), although trials have been undertaken on rope-less system prototypes using timed-release (Partan and Ball 2016) or acoustic-release mechanisms (How et al. 2015; Salvador et al. 2006; Turner et al. 1999). Acoustic releases have been used for some years in an Australian lobster fishery (Liggins 2016), although research on acoustic release technology in this fishery (Hodge 2015) is yet to be published. Acoustic-release systems may be preferable to pre-specified time-release mechanisms which may release ropes before fishers are in the vicinity to haul gear (How et al. 2015; Laverick et al. 2017).

Rope colour changes

Preliminary studies showed northern right whales visually detected red and orange 'simulated' ropes at greater distances than black and green ropes (Kraus et al. 2014; Kraus and Hagbloom 2016), which suggested that changing to red and/or orange commercial fishing ropes may improve their ability to avoid entanglements. However, an over-representation of yellow and orange ropes in humpback whale entanglements in Australia may indicate this species actively target these ropes or, in contrast to right whales, yellow and orange are less visually detectable to humpback whales (How et al. 2015). Minke whales appeared to detect black and white ropes more easily than other colours (Kot et al. 2012).

Stiff ropes

Although increasing rope stiffness could reduce entanglement risk as whales may be able to glide off stiff ropes more easily, there are no published studies on whether ropes with greater stiffness or tension reduce entanglements (Consortium for Wildlife Bycatch Reduction 2014). However, experimental testing using a model of a right whale flipper indicated that stiff ropes may increase injuries at the point of contact (Baldwin et al. 2012).

Conclusions and recommendations

Trawl: conclusions and research needs

Fishery-specific variables and issues need to be considered when designing exclusion devices including the size, biology and behaviour of non-target and target species; size, operation and storage of gear; towing speed; and trawl hydrodynamics in relation to net size/grid and escape hole ratios. Exclusion device grid construction (material, grid angle, bar spacing and size); escape hole size, shape and location (e.g. top or bottom); and the addition of a cover or hood, are all important components that will impact bycatch reduction efficacy (Baker et al. 2014). Appropriately designed exclusion devices have effectively reduced pinniped bycatch in trawl nets. In particular, devices with hard separation grids angled to top-opening escape holes, with a cover or hood held open by a kite and floats, effectively allow pinnipeds to escape and post-escape mortality is likely to be low (Hamilton and Baker 2015a). Loss of dead animals out top-opening holes with covers is considered unlikely, although this requires further verification, ideally by direct assessment of pinniped interactions with exclusion devices in operational fisheries. While there has been limited success with bottom-opening devices, air-breathing marine mammals are probably less likely to escape downwards (Allen et al. 2014) and, furthermore, bottom-opening devices, particularly without covers, may be more likely to have unreported bycatch from dead animals dropping out.

Exclusion devices are not fully effective in mitigating cetacean bycatch in trawl fisheries. Research is required on options for reducing cetacean bycatch including further information on the escape behaviour of dolphin species that interact with nets to inform the optimal location for exclusion devices (probably further forward in nets) and ensure escape options are clear, while retaining target catch (van Marlen 2007). It is inconclusive whether rope or mesh barriers prevent entry of small cetaceans past the fore section of trawls, thereby, reducing bycatch. Furthermore, barriers may reduce target catch to unacceptable levels (Bord Iascaigh Mhara and University of St Andrews 2010).

Net binding may be effective in reducing bycatch risk during the shot, although would only be feasible in operations where the net is removed from the water and brought onto the trawl deck after each trawl. The efficacy of net binding in reducing marine mammal bycatch requires testing, including research to establish the optimal technical specifications to ensure the net remains bound until it reaches depths beyond the diving range of bycatch species. Net binding would only potentially reduce interactions during net shooting and is likely to be ineffective for mitigating bycatch of deep-diving species.

Loud pingers show promise in reducing small cetacean interactions with trawl gear, particularly for common dolphins (Northridge et al. 2011), although may not be effective for bottlenose dolphins (Santana-Garcon et al. 2018). However, development of more robust and operationally manageable devices is required as well as more fishery-specific testing to determine the optimal configuration and spacing of pingers in trawl operations and verification that pingers significantly deter dolphins (Bord Iascaigh Mhara and University of St Andrews 2010; Northridge et al. 2011; van Marlen 2007). Investigating the likelihood of cetacean habituation to pingers as well as the impact of the widespread use of loud pingers on the behaviour, distribution and ecology of cetaceans and other marine species is also needed (Northridge et al. 2011).

Maintaining the shape and structure of trawl nets may be an integral bycatch mitigation strategy, particularly for cetaceans (Santana-Garcon et al. 2018). Auto-trawl systems potentially mitigate bycatch by ensuring the net entrance is always open thereby reducing entrapment risk, although this needs investigation and validation. However, as these systems are routinely used by some trawlers to improve fishing efficiency, evaluation of their mitigation potential in an experimental framework may be difficult.

Purse seine: conclusions and research needs

Management measures, particularly the 'back-down' manoeuvre coupled with 'Medina' safety panels and additional guidance from small boats, increase the safe escape and have significantly reduced the observed bycatch of small cetaceans in tuna purse seine fisheries. However, information is needed on the post-encirclement and post-release survival and health of bycatch species through remote monitoring programs to inform best practice techniques for releasing encircled animals (Restrepo et al. 2014). Although potentially less relevant to marine mammal species, continued research on the development and efficacy of non-entangling FADs is also important.

Longline: conclusions and research needs

There is a lack of technical mitigation shown to be fully effective in reducing marine mammal bycatch in longline fisheries. However, there are indications that catch protection devices, with specific designs for both pelagic and demersal operations, reduce hooking risk for odontocetes. Results have been variable on the impact of different net sleeve devices on target catch rates, and more research is required, particularly to reduce interactions with killer whales that have learnt to get around standard designs in demersal longline operations (Arangio 2012; Goetz et al. 2011; Moreno et al. 2008). In pelagic longline operations, further research is required to refine triggered catch protection device designs, particularly increasing device reliability, and verifying mitigation efficacy in operational fisheries in the longer term (Hamer et al. 2015; Rabearisoa et al. 2012, 2015).

While the use of weak hooks may reduce bycatch in pelagic longlines, this requires further operational testing, including operational feasibility. There is also a lack of information on the post-release health and survival of marine mammals that are injured, retain or ingest hooks, or remain entangled in gear (Bayse and

Kerstetter 2010; Hamer et al. 2012, 2015; Hucke-Gaete et al. 2004; Kock et al. 2006; Werner et al. 2015).

Gillnet: conclusions and research needs

Pingers effectively reduce the gillnet bycatch of some (e.g. harbour porpoises), although not all, small cetacean species, and may be most effective in reducing bycatch of neophobic species with large home ranges (Dawson et al. 2013). Pinger research should include evidence that target species size and catch are not impacted (Barlow and Cameron 2003; Carlstrom et al. 2002; Gearin et al. 2000; Kraus et al. 1997; Larsen and Eigaard 2014; Waples et al. 2013). While the evidence is that harbour porpoises do not become habituated to pingers (Dawson et al. 2013; Palka et al. 2008), further investigations regarding habituation for other cetacean species are needed. More research to understand small cetacean behaviour in response to ‘reactive pingers’ is also required, particularly if they may reduce the likelihood of habituation and potential impacts from marine noise pollution (Leeney et al. 2007). As pingers rely on changing animal behaviour to avoid nets, they should only be implemented after rigorous fishery-specific research on the impacts on all likely bycatch species (Hodgson et al. 2007) and other vulnerable species within the ecosystem. The long-term effects of pinger exposure on small cetaceans, particularly exclusion from key habitat areas, is not well known. Care should be taken when deploying pingers to mitigate bycatch in areas with ecologically important small cetacean habitat, and intensive pinger use in coastal areas should be carefully monitored (Carlstrom et al. 2002, 2009; Kyhn et al. 2015). Operational testing should include research on the optimal positioning and spacing of pingers and, following implementation, ongoing monitoring is required to maintain pinger effectiveness. As commercially available pingers may be prohibitively expensive in some fisheries, more cost-effective solutions are required. The development of more durable pingers with battery change capabilities may help to reduce implementation costs (Crosby et al. 2013).

There have been conflicting results on the effectiveness of acoustically reflective metal oxide nets in reducing small cetacean bycatch, and further research is needed to better understand the mechanism of why some metal oxide nets showed bycatch reduction (Northridge et al. 2017).

Increased research focus is needed on post-release impacts following direct interactions with gillnets. For example, pinnipeds and cetaceans released following entrapments in deep-set gillnets (and trawls) may incur gas embolism that could lead to post-release mortality (Fahlman et al. 2017; Moore et al. 2009).

Pot/trap: conclusions and research needs

Fishery-specific trap guards or ‘excluder devices’ have been effective in reducing the entrapment risk of marine mammals while maintaining target catch rates (Campbell et al. 2008; Konigson et al. 2015; Noke and Odell 2002). The use of “seal socks” may be a potential mitigation option in shallow-water fyke net fisheries, although may not be effective for all pinniped species (Oksanen et al. 2015).

Results on the effectiveness of pingers in deterring large baleen whales from potentially high-risk areas have been variable (Dunlop et al. 2013; Lien et al. 1992; Pirotta et al. 2016) and species-specific investigations of different pingers are required to determine if some designs may be more consistently effective. However, identifying a lack spatial *deterrent* behaviour relative to a pinger in experimental trials may not necessarily mean that pingers would be ineffective in *alerting* marine mammals and reducing operational interactions (McPherson 2017).

‘Rope-less’ buoy systems are a promising mitigation development, although further design refinement and efficacy research is required. Acoustic-release systems may be preferable to timed-release systems but are likely to have higher establishment costs, and research is needed on reliable deployment systems and a device with enough rope for fisheries operating in deep water (How et al. 2015; Partan and Ball 2016; Salvador et al. 2006).

While ropes with reduced breaking strength could substantially decrease whale mortality in fixed gear, research is required on the practicalities and success of using reduced-strength ropes in operational fisheries (Knowlton et al. 2016), and the post-release health and survival of animals that remain entangled in lines or sections of gear (Werner et al. 2015). The effectiveness of weak links in buoy lines needs investigation due to concerns regarding a lack of reduction in whale entanglements following weak link implementation in

USA lobster fisheries (Knowlton et al. 2012; Pace et al. 2014; Van der Hoop et al. 2013). It is noteworthy that weak links are not recommended in some Australian fisheries as disentangling 'anchored' whales from gear has been more successful than locating and disentangling free-swimming whales (How et al. 2015).

Whale responses to different rope colours appears to be species-specific (How et al. 2015; Kot et al. 2012; Kraus et al. 2014; Kraus and Hagbloom 2016). Further species- and fisheries-specific research is needed to test and understand whale detectability of colours in a range of conditions (Kraus et al. 2014).

Final summary and conclusions

Effective technical mitigation measures are a crucial element of any robust, integrated bycatch management program, which usually includes other management directives such as temporal and spatial fishing restrictions and appropriate operational 'codes of practice'. For some gear types and taxa, there are currently limited technical options with strong evidence they effectively reduce bycatch, and substantial development and research of best practice mitigation options is needed to address marine mammal bycatch in many fisheries. For mitigation to be considered effective, a significant reduction in bycatch mortality needs to be demonstrated, together with maintenance of target catch quality and quantity. Fishing industry engagement to ensure design, development and effective implementation of practical solutions is also essential. Therefore, knowledge of the biological and behavioural characteristics of target and bycatch species, temporal and spatial overlap of bycatch species with fishing activities and operational factors is needed (Baker et al. 2014). Determining mitigation efficacy should include species- and fisheries-specific testing with adequate scientific rigour, and a quantitative target to enable efficacy assessment.

The reviewed studies varied greatly in the level and rigour of scientific testing to verify mitigation effectiveness in reducing bycatch. Some measures have undergone controlled studies in a range of conditions [e.g. pingers to reduce harbour porpoise bycatch, Dawson et al. (2013)], while others have not been tested, testing has been inadequate, or experimental design has been inappropriate (e.g. Dawson and Lusseau (2005)). However, testing can be difficult as a technical measure may be implemented as part of a suite of management actions, confounding attempts to test its specific effectiveness in reducing bycatch (Laverick et al. 2017). Ideally, if efficacy is to be efficiently demonstrated, mitigation needs to be tested against a control of no-deterrent, although such trials are often difficult to implement for ethical reasons. Additionally, the logistics of undertaking controlled studies in operational fisheries, including low or sporadic marine mammal interaction rates during trials, may limit the scientific robustness of testing (Dawson et al. 1998; Hamer and Goldsworthy 2006). Obtaining adequate data from comparable controlled experiments may be particularly challenging in trawl fisheries with small numbers of vessels towing a single net. Furthermore, due to the range of variables during fishing (e.g. location, weather, season, ecosystem components), controlled experiments of the same mitigation for the same bycatch species may produce conflicting results in different operations. Technical measures experimentally shown to be effective also require post-implementation monitoring in operational fisheries, and mitigation may not produce the same bycatch decrease in an operational fishery as shown in controlled trials (Orphanides and Palka 2013). Ensuring the ongoing effectiveness of implemented mitigation requires fisheries to maintain adequate observer coverage (either direct observations, or electronic monitoring and review), continue correct deployment of the appropriate measure, undergo frequent expert review of procedures, and continue refinement of measures and strategies as required (Cox et al. 2007; Hall 1998). It is fundamental that fishing effort changes are factored into follow-up assessments of mitigation efficacy. For all fishing gear, obtaining estimates of post-release mortality from direct fisheries interactions is an area of research that requires urgent research attention, although monitoring released individuals this is likely to require a large investment.

Despite these challenges, it is crucial that resources are prioritised towards continued development, scientific testing and subsequent implementation and monitoring of proven, effective technical mitigation measures to ensure the ecological sustainability of commercial fisheries. As marine mammal mortality from fishing gear interactions is likely to increase due to human population growth, increasing industrialisation of fisheries, increasing population sizes of some marine mammal species, and fisheries expanding into new areas (Read et al. 2006), improving and implementing effective mitigation is essential. From a global perspective, improving the environmental sustainability of commercial fisheries requires wider dissemination of successful technologies and knowledge of mitigation techniques and comprehensive engagement of fishers in the development of appropriate bycatch solutions (Hall and Mainprize 2005). Developed countries have a level of obligation to assist developing countries in addressing bycatch issues particularly as many marine mammal species have global distributions. At the least, this should entail the publication of research on mitigation design, development, scientific testing of efficacy (or lack of efficacy) and monitoring of operational deployment. It is hoped that this review contributes to this process by having a 'one-stop-shop' on the current status of mitigation techniques developed and assessed for marine mammal bycatch in commercial trawl, purse seine, longline, gillnet and pot/trap fisheries.

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