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Introduction to the Themed Section: '*Marine Mammal Bycatch and Depredation*'

Introduction

Mitigating bycatch and depredation of marine mammals in longline fisheries

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Demersal and pelagic longline fisheries involve frequent and geographically widespread interactions with many individuals, populations, and species of marine mammals. Animals sometimes suffer mortality and serious injury following these interactions, attracted mainly to longlines as a source of food. This depredating behaviour can have serious consequences for fishermen, especially when they lose valuable catch and face other associated operational and regulatory challenges. Using input from a group of international experts in the science, fishing industry, and government sectors, we produced a list of methods for mitigating depredation and bycatch of marine mammals in longline fisheries, collectively assessed their potential as a solution, and determined priorities for further research. The intention of this review is to help synthesize our current understanding about potential solutions, to provide an introduction to the articles that appear in this themed set of the *ICES Journal of Marine Science*, and to help fishermen, fisheries managers, and research scientists advance solutions to this global problem.

Keywords: bycatch, depredation, longlines, marine mammals.

Background

Longlines are a prevalent form of commercial hook and line gear. They consist of a mainline with attached branchlines containing baited hooks to catch target fish. Mainlines usually extend many kilometres from the fishing vessel that deploys them. Longlines can be distinguished between those that target demersal fish and those targeting pelagic ones. Between 1950 and 2000, longline fisheries produced an estimated annual average of 10% of all recorded fishing catches worldwide by weight, the fifth most of all gear types (Watson *et al.*, 2006). The species catch composition on average consists of the largest (by length) and highest trophic level fishes, such as tuna and swordfish, compared with those caught by other gear. As with all types of fishing, longlines produce considerable bycatch, including many species of endangered megafauna such as sea turtles, elasmobranch fishes, seabirds, and marine mammals (Lewison *et al.*, 2004). Often, bycatch is the principal threat to the recovery of these species and populations (Lewison *et al.*, 2004; Read *et al.*, 2006; Žydelis *et al.*, 2009).

For marine mammals, longline bycatch is a threat to several species and populations including false killer whales (*Pseudorca crassidens*) in the insular Hawaiian Islands, and Risso's dolphin (*Grampus griseus*) and pilot whales (*Globicephala* spp.) in the Northwest Atlantic. However, relative to other fishing gear such as gillnets, considered the most immediate threat to the survival and recovery of many marine mammal species and populations (Reeves *et al.*, 2013), longline fishing generally does not pose as much of a threat, although many individuals suffer mortality and serious injury as a result of the interactions (Gilman *et al.*, 2006; Garrison, 2007). Moral and ethical issues notwithstanding, fishers are mostly concerned by the loss of valuable target catch and other operational concerns due to marine mammal depredation, the term used when predators that are not considered among the primary target catch species, take bait or hooked target fish. Hamer *et al.* (2012) summarized the consequences of odotoncete (toothed whales) depredation to fishers, which are largely economic: (i) damage or loss of catch; (ii) potential for target species to avoid taking baited hooks in the presence of predators; (iii) damage to gear, specifically to hooks or additional components of longlines as marine mammals struggle to break free when hooked or entangled; and (4) unaccounted for catch that may result in erroneous calculations of catch limits or cpue (catch per unit effort), with regulatory implications. In addition, depredation may result in changes to the diet, foraging behaviour, or geographic distribution of marine mammals (Gilman *et al.*, 2006). Finally, some US fisheries are required under the Marine Mammal Protection Act to reduce the number of fishing-associated mortalities and serious injuries to pre-set levels, and failure to attain those levels results in new regulatory restrictions that threaten commercial viability within those fisheries. For example, under the Pelagic Longline Take Reduction Plan for mid-Atlantic longline fisheries, because mortality and serious injury of pilot whales is not nearing zero within the 5-year designated period, fishers are now likely facing a number of pending fishing restrictions as early as 2016.

Interactions between marine mammals and longline operations occur frequently, with reports involving many species throughout the world. Table 1 lists all marine mammal species with written reports of interactions involving hook and line fishing gear, as well as the countries or regions from which these reports originated. Records exist for at least 31 odontocetes (42% of species within this group of cetaceans), 6 (43%) mysticetes, 15 (47%) of pinnipeds, and 2 (50%) sirenians, occurring over a large portion of the global ocean. Percentages were calculated using the list of species maintained by the Society of Marine Mammalogy's Committee on Taxonomy (2014). The list of species interacting with hook and line gear will be biased towards records from commercial longline fisheries, especially those with on-board observers, and the number of species and areas involved are likely higher, given that reporting is not considered comprehensive by geography, over time, or by fishery. Although marine mammal interactions with longline fishing are common, a subset of species are more frequently reported as depredating longline fisheries, and are among those covered by this article theme set: Sperm whales, killer whales, false killer whales, pilot whales, and Risso's dolphin, but also bottlenose dolphin, spinner dolphin, short-beaked common dolphin, and several pinnipeds. Where documentation exists on the types of injuries resulting from encounters, the predominant ones are hooking and entanglement. Hooking is the result of a marine mammal being unable to dislodge itself from the hook, and the animal may remain attached to longline gear or break free, often with the hook still lodged in its mouth or other body part. In at least one case, that of the now presumed extinct baiji dolphin (*Lipotes vexillifer*) from China's Yangtze River, animals could also become snagged by "rolling hooks" on the river bottom (Turvey *et al.*, 2007). Entanglement may occur once an animal is hooked, with lines becoming wrapped around its body or appendages, or it may be that entanglement results even when not predicated by hooking.

With support from NOAA Fisheries' Office of International Affairs, the Consortium for Wildlife Bycatch Reduction based at the New England Aquarium (NEAq) in Boston, MA, USA, organized an international workshop to review the current status of research on reducing bycatch of marine mammals in longline fishing operations, with an emphasis on odontocetes. A four-day workshop was held on the campus of the Woods Hole Oceanographic Institution from 22 to 25 October 2013, with 24 participants representing government, marine scientific institutions, and fishers from the United States, South America, Europe, and Australia (Table 2). The workshop featured presentations giving fishing industry perspectives and collaborative research programmes undertaken in different parts of the world to mitigate marine mammal bycatch and depredation. Many of these presentations are included in this themed article set of the *ICES Journal of Marine Science*.

The studies in this themed article set

The articles published herein are important contributions to understanding the dynamics of marine mammal–longline interactions as well as potential solutions. They include studies from two of the most important long-term collaborations between scientists, fishers, and fisheries managers to address marine mammal depredation in demersal longline fisheries from the Crozet Islands (Guinet *et al.*, 2015) and the Gulf of Alaska (Straley *et al.*, 2015). Although in both fisheries (targeting Patagonian toothfish and sablefish, respectively), neither paper identifies one or more definitive long-term solutions, they highlight the progress towards finding them, and provide convincing arguments that the most promising and sustainable ones will emerge through collaboration between science and industry. Only through these close collaborations is it possible to fully understand how fishing practices contribute to the problem as well as potentially solve it, a process that is the focus of studies by Tixier *et al.* (2015a) and Thode *et al.* (2015). The overriding motivation of collaborative research is for reducing depredation to reduce economic losses, and less borne out of urgency for population recovery of an endangered species or ethical concerns.

More recent regional studies come from the southwest Atlantic, involving both demersal and pelagic longline fisheries (Passadore *et al.*, 2015a, b). They examine physical oceanographic, environmental, and fishing operation variables (e.g. season, temperature, fishing depth, etc.) under which interactions occur, as a means to identify strategies for avoiding or reducing fishing and marine mammal conflicts. The remaining articles evaluate four potential bycatch deterrents, including devices that have not undergone rigorous scientific testing. These include acoustic harassment devices (Tixier *et al.*, 2015b) and passive acoustic devices (O'Connell *et al.*, 2015), which for years have sometimes been used by fishers to deter marine mammal interactions, despite a lack of scientific studies demonstrating their efficacy, and two newer devices that encapsulate caught fish to deter depredation (Hamer *et al.*, 2015; Rabearisoa *et al.*, 2015). A fourth study (McLellan *et al.*, 2015) complements several studies of "weak hooks" to improve selectivity of target catch while reducing bycatch of false killer whales or pilot whales (Bayse and Kerstetter, 2010; Bigelow *et al.*, 2012). It is the first study to examine the potential pulling strength of depredating marine mammals, while also highlighting the variability inherent in hooks used by longliners.

A review of mitigation methods

Building on these studies and on previous reviews, especially by Hamer *et al.* (2012), workshop participants refined a list of methods for mitigating marine mammal bycatch and depredation in longline fisheries, identified which ones had been tested, and then, using expert elicitation, evaluated their potential as a solution to the problem and the extent to which they should be a research priority (Table 3). The criteria used to consider potential promise for mitigation were: degree of reduction in marine mammal depredation

Table 1. Species and countries or regions for which reports exist (1990–2010) of interactions between marine mammals and hook and line gear (commercial and recreational) as categorized by FAO.

	Ocean basin			
Species affected	**South Pacific (incl. Australia)**	**Indian Ocean**	**North Pacific**	**Atlantic**
Odontocetes				
Delphinus sp.	Australia (28); New Zealand (46)	Indian Ocean (83)	West and Central Pacific (90); South Korea (6, 7, 8, 76, 109, 110, 112)	Portugal (88); Western Central Atlantic (70, 71, 124, 129)
Short-beaked common dolphin (*Delphinus delphis*)				Spain (85); Other Mediterranean (115); Western Central Atlantic (119)
Long-beaked common dolphin (*Delphinus capensis*)			South Korea (5, 9)	
Stenella sp.				Western Central Atlantic (120, 121, 129)
Pantropical spotted dolphin (*Stenella attenuata*)	South Pacific (Taiwanese fishery) (47)		West and Central Pacific (117); US Pacific (31, 32, 33, 37); Taiwan (118)	Western Central Atlantic (129)
Atlantic spotted dolphin (*Stenella frontalis*)				Spain (80, 81); Western Central Atlantic (70, 72)
Spinner dolphin (*Stenella longirostris*)	South Pacific (Taiwanese fishery) (47)	Comoros (98); Madagascar (102); Reunion (77)	West and Central Pacific (90, 117); US Pacific (22)	
Striped dolphin (*Stenella coeruleoalba*)	Australia (54); South Pacific (Taiwanese fishery) (47)		West and Central Pacific (117); US Pacific (35, 37)	Spain (81, 85); Other Mediterranean (79, 115) Western Central Atlantic (70)
Common bottlenose dolphin (*Tursiops truncatus*)	Australia (28, 57)	Madagascar (102)	West and Central Pacific (90, 117); US Pacific (22, 31, 32, 33, 35, 37, 70, 73); Taiwan (118)	East Central Atlantic (64); Italy (51) Western Central Atlantic (27, 70, 72, 75, 119, 123, 128, 129, 130)
Indo-Pacific bottlenose dolphin (*Tursiops aduncus*)	Australia (28, 53)	Comoros (98); Reunion (77)		
Indo-Pacific humpback dolphin (*Sousa chinensis*)		Comoros (98)		
Dusky dolphin (*Lagenorhynchus obscurus*)			West and Central Pacific (90)	
South American dusky dolphin (*L. o. fitzroyi*)	Peru (86)			
Atlantic white-sided dolphin (*Lagenorhynchus acutus*)				Atlantic Canada (126)
Pacific white-sided dolphin (*Lagenorhynchus obliquidens*)			US Pacific (62); South Korea (5, 110)	
Globicephala sp.	Australia (28, 52, 53, 54, 55); South Pacific (Taiwanese fishery) (47)	Indian Ocean (66)		Other Mediterranean (115); Western Central Atlantic (24, 68, 69, 70, 71, 72, 73, 74, 75, 100, 119, 121, 124, 125, 129)
Long-finned pilot whale (*Globicephala melas*)	New Zealand (40)			Brazil (96); Atlantic Canada (123); Spain (85)
Short-finned pilot whale (*Globicephala macrorhynchus*)	Australia (42, 55, 57)	Reunion (77)	West and Central Pacific (90, 106); Costa Rica (84); US Pacific (22, 31, 32, 33, 34, 35, 36, 37, 71, 72, 73)	Western Central Atlantic (129)
Risso's dolphin (*Grampus griseus*)		Comoros (98); Reunion (77)	West and Central Pacific (90); US Pacific (22, 32, 35, 36, 37, 72, 73); South Korea (109)	Brazil (103); Spain (81, 85); Other Mediterranean (79); Western Central Atlantic (27, 68, 69, 70, 71, 72, 75, 100, 121, 122, 123, 124, 125, 129)

Irrawaddy dolphin (*Orcaella brevirostrisl*)		Bangladesh (87)		
Ganges river dolphin (*Platanista gangetica*)		Bangladesh (87)		
False killer whale (*Pseudorca crassidens*)	Australia (24, 55); South Pacific (Taiwanese fishery) (47)	Indian Ocean (83)	US Pacific (20, 22, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 47, 70, 71, 72, 73); Japan (93)	Brazil (103); Spain (113); Portugal Azores (60)
Killer whale (*Orcinus orca*)	Australia (10, 24, 108); New Zealand (40, 89, 116); South Pacific (Taiwanese fishery) (47)		US Pacific (2, 11, 14, 34, 62, 70)	Brazil (103)
Melon-headed whale (*Peponocephala electra*)	Australia (42, 56)			
Rough-toothed dolphin (*Steno bredanensis*)			US Pacific (22, 37, 47); Taiwan (118)	
Harbour porpoise (*Phocoena phocoena*)			South Korea (5, 6, 9, 109, 111)	Faroe Islands (94)
Dall's porpoise (*Phocoenoides dalli*)			US Pacific (4, 11, 14, 62)	
Finless porpoise (*Neophocaena asiaorientalis*)			South Korea (9, 76, 112)	
Beluga whale (*Delphinapterus leucas*)				Atlantic Canada (21)
Kogia sp.			US Pacific (37)	Western Central Atlantic (125)
Sperm whale (*Physeter macrocephalus*)	Australia (52, 53, 54, 55, 108); Chile (58, 65); New Zealand (89)		West and Central Pacific (90); US Pacific (2, 14, 16, 31, 33, 62, 73)	Other Mediterranean (92); Western Central Atlantic (121)
Unknown Beaked whale	Australia (53, 54, 57)		Japan (93)	Western Central Atlantic (70, 75, 129)
Northern bottlenose whale (*Hyperoodon ampullatus*)				Atlantic Canada (59, 126)
Blainville's beaked whale (*Mesoplodon densirostris*)			US Pacific (32, 33, 34, 35, 72)	
Gingko-toothed beaked whale (*Mesoplodon ginkgodens*)	Micronesia (43)			
Cuvier's beaked whale (*Ziphius cavirostris*)				Spain (113); Western Central Atlantic (125)
Unknown Odontocete	Australia (24, 42, 55); New Zealand (48); Ross Sea (78); Samoa (47); South Pacific (Taiwanese fishery) (47)	Myanmar (114); Reunion (17); Indian Ocean (66); Malaysia (91)	West and Central Pacific (90); Costa Rica (44); US Pacific (22, 31, 70, 72, 73)	Uruguay (29); South Georgia (78); Spain (85); Nigeria (91); Cameroon (91); Sierra Leone (91); Other Mediterranean (115); Western Central Atlantic (70, 119)
Mysticetes				
Southern right whale (*Eubalaena australis*)	Australia (99)			South Africa (25)
North Atlantic right whale (*Eubalaena glacialis*)				Western Central Atlantic (119)
Bryde's whale (*Balaenoptera brydei*)			US Pacific (72)	
Humpback whale (*Megaptera novaeangliae*)	Australia (52, 57); Ross Sea (78); Cook Islands (34)	Madagascar (101)	West and Central Pacific (9, 100); Mexico (45); US Pacific (1, 2, 13, 50, 61, 62, 71, 73, 106)	Western Central Atlantic (119, 120)
Minke whale (*Balaenoptera acutorostrata*)	Ross Sea (78)		South Korea (7, 9)	Argentina (107); Spain (82) Western Central Atlantic (120, 127)

Continued

Table 1. *Continued*

	Ocean basin			
Species affected	**South Pacific (incl. Australia)**	**Indian Ocean**	**North Pacific**	**Atlantic**
Gray whale (*Eschrichtius robustus*)			US Pacific (13)	
Unknown Balaenopterid	Australia (28, 108); New Zealand (41)		West and Central Pacific (90); US Pacific (73, 100)	Brazil (97) Western Central Atlantic (119)
General cetacean				Spain (115)
Pinnipeds				
New Zealand fur seal (*Arctocephalus forsteri*)	New Zealand (18, 19, 104, 105)		West and Central Pacific (90)	
Australian fur seal (*Arctocephalus pusillus*)			West and Central Pacific (106)	
Subantarctic fur seal (*Arctocephalus tropicalis*)				Uruguay (29)
South American fur seal (*Arctocephalus australis*)				Uruguay (95)
California sea lion (*Zalophus californianus*)			US Pacific (38)	
Steller sea lion (*Eumetopias jubatus*)			US Pacific (2, 3, 4, 12, 14, 15, 16, 49, 62, 63)	
New Zealand sea lion (*Phocarctos hookeri*)	New Zealand (19)			
Atlantic harbour seal (*Phoca vitulina*)				Western Central Atlantic (27)
Pacific harbour seal (*Phoca vitulina richardii*)			US Pacific (4, 22, 62)	
Spotted seal (*Phoca largha*)			US Pacific (4)	
Gray seal (*Halichoerus grypus*)				Faroe Islands (67)
Ribbon seal (*Histriophoca fasciata*)			US Pacific (15, 62)	
Hawaiian monk seal (*Monachus schauinslandi*)			US Pacific (22, 23)	
Northern elephant seal (*Mirounga angustirostris*)			US Pacific (62)	
Northern fur seal (*Callorhinus ursinus*)			US Pacific (4, 16)	
Leopard seal (*Hydrurga leptonyx*)	Australia (24)			
Unknown pinniped	Australia (24)			
Sirenians				
Dugong (*Dugong dugon*)	Australia (26)	Comoros (91, 98)		Cameroon (91)
Florida manatee (*Trichechus manatus*)				Western Central Atlantic (128)

Reports grouped by Ocean Basin. Numbers refer to references (see Supplementary material). US Pacific includes the west coast, Gulf of Alaska, Hawaii, and Pacific Island Territories, inside and outside the EEZ. The US Atlantic includes the Gulf of Mexico and Caribbean. An interaction involving each a "sea bear" and a "black fish" was excluded from the list. A harbour porpoise record for S. Korea from the S. China Sea (Reference #9) is likely outside the species' geographic range.

Table 2. Participants of the International Marine Mammal—Longline Bycatch Mitigation Workshop, 22–25 October 2013.

Participant	Affiliation
Terri Beideman	Blue Water Fishermen's Association, USA
Luciano Dalla Rosa	Universidade Federal do Rio Grande, Brazil
Dan Falvey	Gulf of Alaska, Myriad Fisheries, USA
Christophe Guinet	Centre d'Etudes Biologiques de Chizé, France
John Hall	Hawaii Longline Association, USA
Lanni Hall	NMFS-NER, Protected Resources, USA
Derek Hamer	Australian Marine Mammal Center, Australian Antarctic Division, Australia
David Kerstetter	Nova Southeastern University, USA
Scott Kraus	New England Aquarium, USA
Kristy Long	NMFS Office of Protected Resources, USA
Kate McClellan	Consortium for Wildlife Bycatch Reduction, NEAq, USA
William McLellan	University of North Carolina—Wilmington, USA
Aran Mooney	Woods Hole Oceanographic Institution, USA
Victoria O'Connell	Sitka Sound Science Center, USA
Simon Northridge	University of St Andrews, UK
Megan Peterson	University of Alaska—Fairbanks, USA
Njaratiana Rabearisoa	Institut de Recherche pour le Développement, France
Andy Read	Duke University, USA
Eduardo Secchi	Universidade Federal do Rio Grande, Brazil
Jan Straley	University of Alaska, USA
Aaron Thode	Scripps Institution of Oceanography, USA
Paul Tixier	Centre d'Etudes Biologiques de Chizé, France
Tim Werner	Consortium for Wildlife Bycatch Reduction, NEAq, USA
Nina Young	NOAA Office of International Affairs, USA

and bycatch; effect on target species catch; perceived technological feasibility; perceived risk of unintended consequences; and fishing practicality. Determination of a method's research priority considered the following criteria: how amenable it was for research or field trials; if there was a perceived need for assessment; the level of technological development and statistical power needed for the research project; the potential benefits for endangered species or a high value fishery; applicability across multiple fisheries; and the quantity and quality of previous research. Descriptions of each of these proposed methods follows, including some important observations about them made by one or more individuals at the workshop.

Spatial management methods

Static closures

Areas closed to fishing permanently or for set periods of the year, for designated gear types or all gear types; closures are not triggered by a particular event (such as an attained catch quota) (Dunn *et al.*, 2014). These closures generally would need to be large, based on animal movements that are geographically broad. This may greatly impact fisheries by closing off much of the fishing area. They would be infeasible where marine mammal habitat and fishing grounds largely overlap in time/space with limited or no possibility for relocating fishing. The time (duration and period covered) and area involved will greatly influence the degree to which these closures are effective. Too few studies exist on these closures—particularly on the optimization of cost/benefit—although they are often the default regulatory measure.

Triggered closures

Entire fisheries are closed, usually for the remainder of the fishing season, following a recorded event or threshold (such as depredation or bycatch thresholds) (Dunn *et al.*, 2014). More flexible than static closures, triggered closures provide incentives to comply with other existing measures and pursue cooperative research. Better communication technology and protocols would improve their utility and effectiveness.

Move-on rule

Similar to triggered closures, except the closure applies only to a specific area and/or a specific period within a particular fishing season, and may involve one or more gear types (Dunn *et al.*, 2014). Vessels are expected to move out of a specified area once a triggering event has occurred. Difficult to enforce, this method needs all vessels to adhere to restrictions to ensure success. Research could focus on their efficacy and the decision-making process for when and how they become triggered.

Predictive forecasting

The identification of conflict-prone regions through habitat modelling to identify areas in which fishing-marine mammal conflicts might be avoided in the future (Passadore *et al.*, 2012, 2015a, b; Peterson and Carothers, 2013). This approach involves a high level of analytic effort with little demonstrable gains to date (e.g. Hawaii's False killer whale Take Reduction Plan). There can be high variability in the quality of data used by models, in the different equipment available to researchers for measuring them, and the analytical methods used for targeting high conflict zones. Relative to other mitigation techniques, this could be a relatively low-cost one to the industry. Long-term data series are needed to produce more reliable forecasts.

Near real-time monitoring

The near instantaneous detection of marine mammal presence within fishing locations using satellite tags or passive acoustic monitoring (Thode *et al.*, 2006). Scale-dependent; it would be most effective where a few serial depredators occur (such as killer whales in the Crozet Islands), and less so where many occur (such as pilot whales in the northwestern Atlantic). The cost can be prohibitively high. It is challenging to disseminate information across an entire fleet, but where this has been done, it has been effective. One potential limitation is the relatively short operational life of tags.

Acoustic methods

Acoustic jamming

Reduce or interfere with the echolocation ability of animals in detecting prey items (Mooney *et al.*, 2009). Marine mammals are extremely adaptable and intelligent, and would have a high likelihood of finding an easily obtainable food source, which suggests the approach is unlikely to be successful. Another concern is by disabling echolocation, bycatch rates might be increased. Nonetheless, there is considerable interest within members of the fishing industry to further examine this method. Research would be useful for explaining the nature of the interaction (how cetaceans interact with target species), and might help to develop an effective deterrent.

Acoustic harassment (deterrence)

Deter the animals' approach to gear by causing physical discomfort or negative behavioural responses to predator signals (Götz and Janik, 2014). Although its potential promise as a mitigation technique was voted almost unanimously low, the group recognized there is a high degree of variability of devices within this category. Interestingly, many fishers employ these devices, although scientific

Table 3. Methods for reducing marine mammal depredation and bycatch on longline fishing gear, including whether or not they have been experimentally tested, whether or not there is evidence showing they are effective, and an assessment by experts on their potential as a deterrent and priority for further research.

Method	Scientifically evaluated?	Currently effective?	Potential promise as a mitigation measure?	Vote (high/med/low)	Research priority (high/med/low)	Vote (high/med/low)
Static closures	No	Unknown	Medium	4/10/6	Medium	1/14/4
Triggered closures	No	Unknown	Medium	7/11/1	Medium	5/12/1
Move-on rule	Yes	Yes	Medium	8/11/0	Medium	4/14/3
Predictive forecasting	No	Unknown	Low	2/7/9	Medium	1/15/5
Near real-time monitoring	No	Yes	Medium	1/17/1	Medium	7/13/1
Acoustic jamming	Yes	No	Low	0/4/14	Low	0/9/11
Acoustic harassment (deterrence)	Yes	No	Low	0/1/19	Medium	4/11/3
Acoustic harassment (prevent spread)	No	Unknown	Low	0/0/20	Low	0/0/20
Acoustic decoy	Yes	Unknown	Low	1/9/12	Medium	2/11/7
Catch protecting gear	Yes	Yes	Medium	5/13/0	High	21/0/0
Camouflage	Yes	No	Low	0/6/14	Low	0/7/13
Terminal gear modification	Yes	Yes	High	15/6/0	High	16/3/0
Magnetic fields	No	Unknown	Low	Consensus	Low	Consensus
Electric fields	No	Unknown	Low	0/1/19	Low	0/1/19
Increasing hauling speed	Yes	Yes	Medium	4/15/0	Medium	1/11/6
Alternative gear types	Yes	No	Medium	0/17/3	Medium	1/16/2
Set length	Yes	Yes	Medium	6/14/0	Medium	6/12/0
Time of day	Yes	No	Low	0/0/20	Low	Consensus
Season variability	Yes	Yes	Medium	Consensus	Medium	0/10/9
Reduce long-range cues	No	Unknown	Medium	3/15/0	High	Consensus
Chemical	No	Unknown	Low	0/1/17	Low	Consensus
Physical harassment	No	Unknown	Low	Consensus	Low	Consensus
Lethal removal	No	Unknown	Low	1/1/17	Low	Consensus
Offal retention	No	Unknown	Low	0/8/9	Low	0/2/17
Offal discard	No	Unknown	Low	0/3/16	Low	0/2/17
Decoy and blank sets	Yes	Yes	Low	0/8/11	Low	0/2/17
Collecting fish at depth	No	Unknown	Medium	0/11/8	Medium	7/9/3
Set geometry	No	Unknown	Medium	0/11/6	Low	0/7/10
Change bait	No	Unknown	Low	0/3/16	Medium	0/11/6
Safe handling and release	No	Unknown	Medium	8/10/2	Low	9/8/1

Areas shaded green were rated high as a potential mitigation method and as a research priority; yellow shading was used where both were rated medium, and red where both were low. Non-shaded rows were ranked differently in these two categories. High, medium, and low rankings were based on majority rule voting. Voting involved a form of expert elicitation, in which a first vote was taken and followed by a discussion in which individuals explained their rationale for their votes. The vote was then retaken, and recorded. Vote tallies ranged from totals of 17–22, the result of some individuals being absent from the room when votes were taken or deciding to abstain.

evidence of their efficacy is lacking, and under certain conditions, it is clear they do not work. It is extremely difficult to conduct an experiment in a pelagic longline fishery and get statistically valid results. Habituation is also possible though largely unexamined (but see Tixier *et al.*, 2015b).

Acoustic harassment (prevent spread of depredation habit)

Sound emissions under this approach focus only on naïve populations, are activated only in response to echolocation signals from marine mammals, or involve variable frequencies or emission types (Thode *et al.*, 2012; Gasco, 2013). So far there are no demonstrated effective deterrents available for preventing spread, and enforcement would be difficult. Our understanding about how behaviour spreads throughout marine mammal populations is still unclear and would be needed before using this type of acoustic harassment as a deterrent.

Acoustic decoy

Divert or delay the approach of marine mammals from fishing operations (Thode *et al.*, 2012, 2015). Even if the exclusion time from a fishing operation was of short duration, it could have benefits if effective at certain periods such as while hauling. Preliminary experiments suggest it is worth additional testing, although its use would involve a high cost to fishers. It is highly probable that given the intelligence of marine mammals, they might overcome any temporary deterrent effect that might be created.

Physical methods

Catch protecting gear

A triggered device that encapsulates target catch, such as in dangling chains or plastic filaments, to deter depredation (Hamer *et al.*, 2012, 2015; Rabearisoa *et al.*, 2012, 2015). Likely more effective in deep water demersal fisheries because fish only need to be protected during hauling (not soaking), and could break the reward cycle to suppress depredation. Feasibility is probably less for pelagic fisheries because of an anticipated increase in labour, crew, and cost, but operational concerns may be overcome with additional research (see Hamer *et al*., 2015). Transferability potential is high among similar fisheries. Research was unanimously recommended to indicate whether this method might reduce or stop depredation.

Camouflage

The use of bubble screens or attaching components such as acrylic beads that simulate the acoustic signal of target catch, with the intention of confusing a marine mammal from detecting the actual catch (Straley *et al*., 2013; O'Connell *et al*., 2015). This is a relatively inexpensive tool, but marine mammals are likely too intelligent for this to be effective. Many such passive reflective devices have been tested and not worked. However, previous work has shown what the whale "sees" when echolocating on target fish, and they do avoid acoustic profiles of snarls and rockfish, so it cannot be entirely ruled out.

Terminal gear modifications

To date, this has involved decreasing the bending strength of the hook to a level where it straightens and facilitates release when pulled by a marine mammal, while remaining strong enough to retain target catch (Bayse and Kerstetter, 2010; Bigelow *et al*., 2012). This method is mainly applicable in pelagic longlines. Target species catch could be affected if the terminal tackle is not optimal for retaining it. Where no other deterrence is possible, it may be the only solution for minimizing bycatch of small odontocetes. It is highly practical because it only involves minimum change to current practices, and does not require knowledge of how the animals cue into gear or fishing operations. This technique can reduce bycatch but not depredation. An important research priority should be on understanding the severity of injury to animals that have been hooked, and those that escape from weak hooks (see McLellan *et al*., 2015). Post-hooking mortality is poorly known.

Magnetic fields

No indication that these would deter marine mammals, and not very practical onboard (magnets attract hooks). There may also be unintended consequences to other animals that are highly sensitized to magnetic fields, such as elasmobranch fishes.

Electric fields

Preliminary results with seals might argue for further examination, but much exploratory research is needed before it could be considered as a potential mitigation measure. Operational difficulties working on boats are very likely.

Other methods

Increasing hauling speed

Reduce the probability that marine mammals can take target catch by "outrunning" them (see Tixier *et al*., 2015a). This technique would be more applicable to demersal longlining where fish are only depredated during haulback. More fish might be lost by falling off hooks when haul speed is increased.

Alternative gear types

Switching out longline gear for another gear type altogether (e.g. pots) that might be commercially viable but significantly reduce marine mammal bycatch and depredation (Hanselman *et al*., 2009; Peterson and Carothers, 2013). Switching gear types would likely entail the need for new regulatory and permitting requirements. There would also be operational concerns for a vessel needing to alter gear. Depredation rates may get so high in a specific fishery that switching gear might be the only option. Potential unintended consequences are anticipated, and the impacts on target species abundance could be significant if the alternative gear is more efficient. Previous research to help develop alternative gear has not been particularly successful with longlines.

Set length

Reducing the length of mainlines to reduce the portion of gear available for depredation (Garrison, 2007; Tixier *et al*., 2010). Applicable for both demersal and pelagic longlines. This is operationally feasible, and splitting gear into more sets reduces depredation anecdotally, but will increase handling time costs. Where effective, it might only be short-term solution.

Time of day

Setting gear when marine mammals are less active. This tactic is infeasible for some fisheries if the target species and marine mammals are both actively feeding at the same time.

Season variability

Set gear when marine mammals are less likely to seasonally co-occur in fishing areas (Tixier *et al*., 2010). Not applicable in all fisheries, but could be very successful, for example, with killer whales in the Crozet Islands. Could reduce catch and result in other unintended consequences, but should be relatively easy to test.

Reduce long-range cues

Change fishing practices to reduce the probability that marine mammals detect fishing activity, such as alteration of acoustic footprints or period of vessel loitering (Gilman *et al*., 2006; Thode *et al*., 2007). Whales seem to home in on vessel noises, so quieting vessels could be effective. Understanding the extent to which marine mammals use cues for finding vessels would be required to evaluate the potential of this technique.

Chemical

Reduce palatability of bait. Making bait unpalatable could make marine mammals sick and might be politically unpopular, as well as repel target species. Conditioned taste aversion could be a useful area of research. Focusing on bait does not address depredation on target catch, and this technique has not proven very effective for other non-target species such as California sea lions (Gearin *et al*., 1988).

Physical harassment

Exclusion of marine mammals as a depredation threat by using pyrotechnics or other non-acoustic harassment methods (Dahlheim, 1988). There is obvious potential for physical harm to marine mammals, which may be too attracted to preying on catch anyway to be effective.

Lethal removal

The direct targeting and killing of serial depredating animals. Hundreds of Icelandic killer whales were reported lethally removed in the 1950s to protect longliners (Mitchell, 1975). Small numbers of serial depredators could be removed, which could reduce depredation rates; however, because this behaviour appears easily learned within a population, it probably would have limited effectiveness. Unintended consequences could be very high for cetacean populations. The practice of killing depredating marine mammals appears widespread around the world at least from anecdotal accounts, but is not widely publicized for obvious reasons.

Offal retention

Retaining rather than discarding offal overboard during active fishing to reduce the attraction marine mammals may have to fishing vessels for feeding opportunities. It is practically infeasible for some vessels to retain offal for long periods, and the practice may involve regulatory issues. The removal of offal from the water may only create a marginal effect for marine mammals that already associate longliners with feeding.

Offal discard

Offal discarded at locations and times away from active fishing might focus marine mammal feeding away from primary catch. This practice would be most applicable where depredating cetaceans already occur near fishing operations and are attracted to discharged offal. It may, however, also reinforce the association between vessels using this method with a food reward.

Decoy and blank sets

Deployment of incomplete longline sets (e.g. lacking hooks) that might appear as actual fishing sets to trick marine mammals into interacting with the decoys rather than actual sets, and over the long-term decrease their motivation to seek out active sets (Thode *et al.*, 2012). This technique would incur significant increases to fishing expenses and labour with questionable benefits, but would be easy to test experimentally.

Collecting fish at depth

Using devices that can collect or protect target catch at depth before they become accessible to cetaceans (Arangio, 2012). The approach would be limited to demersal longlining. It could be impractical for a lot of vessels, and very expensive. Over time, it could eliminate the incentive for cetaceans to interact with demersal longline fisheries, by eliminating the reward.

Set geometry

Altering or mixing longline deployment schemes (e.g. depth, orientation, split sets) to reduce marine mammal interactions. Very fishery-specific, and may be infeasible depending on fishing area. Should be fairly easy to investigate. This approach would likely only apply to anchored gear.

Change bait

This approach has limitations because most depredation occurs with target catch and not the bait. One exception may be with smaller cetaceans, which tend to take bait more often than larger whales. Changing bait has been shown to affect target catch and bycatch levels of sea turtles (Watson *et al.*, 2004). Unintended consequences with target catch and other taxa may be expected. Could be a relatively easy research project to implement. Artificial baits may be cost prohibitive and ineffective for target species.

Safe handling and release

The use of techniques such as de-hooking and hook cutters to enhance survival post-capture. There is a perceived need for these practices, particularly among many fishers because of regulatory concerns (e.g. off the east coast of the United States). These techniques are thought to increase survival, although post-release survival remains largely unknown.

Summary

Some of the techniques reviewed would be appropriate for both pelagic or demersal longline fisheries, while others apply mainly to one or the other. For example, the use of weak hooks, in which hook strength is reduced to a level that can still retain target catch while caught cetaceans can release themselves by straightening the hook, were conceived mainly for pelagic fisheries with high hooking interactions of species such as pilot whales and false killer whales. The use of advanced technology for collecting hooked fish at depth is more relevant to demersal fisheries.

In discussions of these techniques, workshop participants continually shared several observations that should serve as important guiding principles in advancing solutions. Among these is the importance of considering potential and serious unintended consequences from using such techniques. There are many, including possible increases in mortality and serious injury of marine mammals or different non-target animals including elasmobranchs, seabirds, and sea turtles. Certainly, the objective of implementing one or more of these methods should not be to replace one problem with others. A number of methods also raised ethical concerns, because they inflict pain and suffering on marine mammals, and sometimes involve purposeful killing. In at least one case, that of acoustic harassment devices, a major disconnect exists between industry and science, with the former recognizing the potential of using acoustic methods for deterring depredation, while researchers lack scientific evidence showing they work (see Tixier *et al.*, 2015b). This means that the pursuit of solutions do not always involve three "check marks" (work for bycaught species, work for fishers, and have negligible or manageable unintended consequences), but instead represent a more complicated process.

The consensus regarding the best process for moving forward is the one that fully engages fishers and scientists working in collaboration, as well as engineers with expertise in the development and testing of deterrents, and technologies useful for studying the problem. This basic inclusive approach is a familiar mantra in bycatch reduction, but it is based on examples from other fisheries in which the most effective techniques emerged from these kinds of collaborations. Typically, solutions emerge after many years—sometimes decades—of collaborative research, and maintaining sustained funding over long time frames is a major challenge.

Major knowledge gaps

Survivability after hooking or entanglement remains a major gap in our knowledge, hindering an accurate accounting of serious injury and mortality to marine mammals occurring from interactions with longline fishing operations. Furthermore, it can create misleading information about techniques that may have the most promise as solutions. It will be difficult to determine whether or not a particular method is effective if its full impact cannot be measured.

A better understanding about the behaviour of marine mammals near longlines would better inform the development of deterrents. Specifically, how are they locating the gear—with acoustic or visual cues, or perhaps both? What characterizes the degree of interaction with different components of the gear, and how much does bait vs. target catch contribute to interactions? Depredation behaviour appears learned, and, if so, how does it spread and how might it be "unlearned"?

Conclusion

The intention of the studies in this themed article set, together with this expert review, is to inform longline fishing operators, fisheries managers, engineers, and research scientists in advancing solutions to this long-standing problem. The articles included herein, and those reviewed for this introduction, represent an incremental learning process that has occurred over many years to understand the nature of the interactions, as well as the potential solutions. The majority of seemingly good ideas for mitigation of fisheries bycatch and depredation rarely realize their promise, although the collective body of research to which they contribute continues to open up new ideas and assist in the refinement of methods that should move us closer to finding more effective deterrents. Although a simple and quick solution to these problems would be welcome, especially for those fisheries that are impacting the most threatened marine mammals and face the most severe economic consequences, a more sensible approach is to draw from the body of work undertaken to date, and continue to engage in collaborative research between science and industry in evaluating the potential tools so far proposed that appear the most promising.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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