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Acoustic methods of reducing or eliminating marine mammal–fishery interactions: do they work?

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ABSTRACT

Although a great deal of effort has been directed toward attempts to use sound to reduce or eliminate marine mammal incidental capture in fisheries and predation on fish, there is little evidence of the effectiveness of such methods in solving marine mammal–fishery conflicts. Passive methods of increasing a net's reflectivity are hypothesized to result in lowered marine mammal bycatch rates, by making it easier for the animals to detect and avoid nets. However, so far, substantial decreases in cetacean bycatch have not been demonstrated, either from comparisons of catch rates in commercial fisheries or from observational studies of deterrence. The goal of active acoustic methods is the production of sound to warn the animals of the gear, or to cause them to leave the area. Various attempts have been made to use active methods to deter pinnipeds from areas of fishing activity (generally to avoid predation on the fish), and to warn cetaceans of the presence of a net (to reduce incidental catch). Net alarms have greatly reduced large whale entrapment in fish traps in Canadian waters, but despite extensive testing, have generally not shown similar success in reducing small cetacean bycatch in a number of gillnet fisheries. Overall, most attempts to use sound to reduce or eliminate marine mammal–fishery interactions have been based upon trial and error, with few controlled scientific experiments, making evaluation of the effectiveness of these methods difficult. Much more basic research on marine mammal echolocation behavior and on behavioral interactions between marine mammals and fisheries needs to be done before substantial success using acoustic methods can be expected. Copyright © 1996 *Elsevier Science Ltd.*

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1. INTRODUCTION

Marine mammal–fishery conflicts are widespread where marine mammal and human distributions overlap, and the conflicts take many forms.[1–3] Incidental catches of marine mammals in fisheries (especially those using gillnets) are of particular concern. A 1990 international workshop and symposium on cetaceans and passive fishing techniques, primarily gillnets, reviewed the nature and extent of these interactions worldwide.[4]

Many marine mammal species use sounds to communicate, to locate and capture prey, and to evaluate physical features of their environment.[5] In the past several decades much has been learned of the auditory capabilities of marine mammals. Unfortunately, there is still much more that needs to be learned about the ways in which marine mammals use their senses to interpret their natural environment, and about their reactions to human activities such as fisheries.

A great deal of time and money has been spent trying to modify fishing gear so that it is more detectable acoustically, and to develop techniques using sounds that will help marine mammals detect fishing nets. However, studies done to date have produced little evidence that sound can be used to prevent or significantly reduce the incidental take of marine mammals. It is not clear whether the lack of success is a product of inadequate study, poor experimental design, improper equipment, or misconceptions concerning the potential use of sound to prevent or reduce the incidental take of marine mammals in fisheries.[6–8]

The purpose of this paper is to identify and conduct a preliminary assessment of the strengths and weaknesses of studies that have been, or are being, done to determine whether acoustic reflectors, sound generators, and other acoustical devices and techniques can be used to prevent or significantly reduce the incidental catch of marine mammals in commercial fisheries. In addition, we attempt to identify the critical remaining uncertainties involved in such research, and suggest the types of studies required to resolve these uncertainties. Although this paper reviews work directed at reducing incidental catch of marine mammals in commercial fisheries, much of the acoustic deterrent work with marine mammals has been aimed at reducing predation of marine mammals on fishing activities. These studies, although of secondary importance to this review, are relevant and are discussed where applicable.

2. REVIEW OF THE LITERATURE

2.1. Passive methods of reducing fishery interactions

Passive methods attempting to reduce fishery interactions do not involve the production of sound, and include various types of modifications to increase the detectability of nets to odontocete cetaceans, which all presumably have echolocation capabilities.[5] Table 1 provides a summary of attempts to use passive methods to reduce capture rates of cetaceans in commercial fisheries. There may be several explanations for the fact that odontocetes are entangled in nets despite their echolocation abilities. First, some net materials may be acoustically transparent to the echolocating animal.[9] Second, animals may not be echolocating constantly and thus may be unaware that a net is present.[10,11] Third, animals may detect the net, but be unaware of the potential danger.[12] Finally, they may be aware of the danger, but simply make mistakes.[8]

Passive methods can only be expected to be effective when the animal is actively using its sonar. This may be particularly important, because the percentage of time that most small cetaceans use their echolocation is not known, but for at least some species it may be rather small. For instance, it has been found that Hector's dolphins (*Cephalorhynchus hectori*) are often silent, and transient killer whales (*Orcinus orca*) in the Pacific Northwest, which use stealth to hunt marine mammals, are often relatively quiet.[10,13]

2.1.1. *Net modifications*

In the past several decades, millions of dolphins have been killed in tuna purse seine nets in the eastern tropical Pacific (ETP).[14] Target strengths[15] of the multifilament webbing types used in tuna purse seines have physical characteristics that apparently render them detectable to dolphins.[16] Indications from behavioral studies in the ETP also indicated that pantropical spotted (*Stenella attenuata*) and spinner (*S. longirostris*) dolphins are able to detect tuna purse seines.[17] Work aimed at reducing dolphin takes in tuna nets has therefore focused on aspects other than increasing the acoustic detectability of nets. Instead, it has generally been in the form of modifications of the fishing gear and practices to release dolphins from the net without them contacting the mesh, or preventing them from becoming entangled if they do.[18–20]

Gillnets, which are designed to be invisible to the target fish or invertebrate species, generally use finer twine than purse seines. Early indications that monofilament webbing used in many gillnet fisheries has a very low target strength were interpreted to suggest that the nets were probably undetectable to porpoises.[9] Knots in the webbing were found to give relatively stronger echoes than strands of monofilament line.[21] Spinner dolphins, when tested in captivity, apparently did not detect panels of monofilament webbing prior to contact.[22]

More recent studies, however, suggest that target strengths of monofilament nets, although low, are likely to be detectable to small cetaceans, at least under some conditions.[6,23,24] Several earlier papers also indicated or suggested that porpoises might have the ability to detect monofilament nets,[25,26] and most recent work supports this.[4,6,12,27,28] However, the target strength of nets probably has to be very high to be perceived when a small cetacean's echolocation is 'locked on' to a target, using a pulse repetition rate suited to that target, such as commonly occurs when pursuing prey.[24,29] This phenomenon is known as 'range-gating', and it may be a significant factor in cetacean entanglement in gillnets.[8]

Different components of a gillnet have varying reflectivities. A study of the acoustic reflectivities of different components of a gillnet demonstrated that floats and, to a lesser extent, the leadline gave the strongest echoes.[21] A bottlenose dolphin (*Tursiops truncatus*) tested in captivity apparently could not detect monofilament webbing with its echolocation, but could detect floatlines.[30]

Several webbing modifications have been explored as possible methods of increasing the acoustic reflectivity[31] of gillnets to cetacean echolocation, thereby making nets easier to detect. This could result in lower entanglement rates if the animals have a natural tendency to avoid novel objects (as, for example, suggested by observations of captive dolphins),[32] or if they will be more cautious when they are aware of a potential barrier in the area.

Incorporation of panels of multifilament webbing into the middle of the monofilament net was tested in the Japanese salmon mothership driftnet fishery in the North Pacific, which had an incidental take of Dall's porpoises (*Phocoenoides dalli*). Using data from the fishery in 1986 ($n = 272$ sets), researchers found a 28% lower bycatch rate of Dall's porpoises than for monofilament nets (significant at the 0.05 level),[28] but for 1987 ($n = 628$ sets) a smaller decrease (9%) was found, which was not significant.[33] However, these catch rates are based on data collected by fishermen, and not by independent observers.

Starting in 1983, a major effort to increase the acoustic reflectivity of Japanese salmon driftnets involved the use of 3–5 strands of hollow monofilament (also called 'air tubes'), incorporated into the middle or upper portion of the nets. Take rates of Dall's porpoises in these modified nets were reported to be lower than for standard nets,[33–38] but results were not consistent.[8] Here, again, it is important to note that data were not collected by independent observers. Decrease rates of 8–20% and 28% were reported.[28,33] Data collected by US fisheries observers ($n = 884$ standard sets, 474 modified) indicated a small (17%) reduction in take rate for nets with hollow tube mesh.[39] The statistical significance of these data, pooled over several years, was not tested, but when analyzed on a yearly basis, results were mostly insignificant.[39] The latter conclusion[39] may be the most reliable, because it is the only one based on a large sample of data collected by independent observers.

Interestingly, hollow monofilament panels of the type used in the Japanese salmon mothership fishery actually may have lower target strengths than the regular monofilament nets.[21] It is possible that the hollow tubing did not maintain its integrity during fishing and handling; however, the actual reasons for the loss in target strength are not known. Thus, any significant decreases in take rates with this type of net would be surprising.

2.1.2. *Add-on reflectors*

Objects with high acoustic reflectivity have been attached to nets in an attempt to enhance the detectability of the gear to a cetacean's echolocation. The addition of echo-spheres, and other objects not normally part of the fishing gear has been suggested to increase the acoustic reflectivity of Japanese salmon driftnets and thereby reduce the incidental entanglement of Dall's porpoises.[9,40] This idea has been extended to other fisheries as well (see below).

Recent experimental work in test tanks has supported the concept that add-on reflectors (polyester rope, bead chain, and surgical tubing) can increase the acoustic target strength of gillnets.[6,41] Plastic air-filled floats used as acoustic reflectors effectively increased detectability of albacore tuna driftnets (measured with a 100 kHz sidescan sonar).[42] However, some air-filled reflectors may cause other problems, as they may provide an echo that is similar to that of prey items, thereby attracting small cetaceans to the net and increasing their chances of entanglement.[43]

Several studies have tested the effect of nets with passive reflectors on cetacean bycatch rates. Australian researchers used 4 mm metallic bead chain and 8 mm air-filled plastic tubing as add-on acoustic reflectors to pelagic gillnets used in northern Australian seas.[44] This fishery had an incidental kill of bottlenose and spinner dolphins. Despite some early promise, a more unbiased test ($n = 39$ sets with both modified and unmodified nets) resulted in higher catch rates in the modified nets.[44] Thus, neither experimental gear type was considered to be effective in reducing small cetacean bycatch.

Add-on reflectors (25 cm^2 plasticized aluminum foil squares, 235 mm diameter aluminum discs, and 0.16 mm stainless steel wires) have been placed on shark nets in South Africa, in an attempt to reduce the bycatch of bottlenose and Indo-Pacific humpback (*Sousa chinensis*) dolphins.[45] Tests of their effectiveness were discontinued because of logistical difficulties (such as corrosion and wave action damage to the gear). Also, catch per unit effort[46] of dolphins was so low that prohibitively large sample sizes would have been required to determine whether there was a statistically significant reduction in take rate.

Vinyl string (diameter not reported), 6.7 mm rope, and 15 cm^2 blister sheets were woven into Japanese salmon driftnets to increase their reflectivity. Some porpoises were taken in the modified nets, but no systematic data were collected on take rate relative to unmodified nets.[47]

Currently, passive acoustic reflectors (same as those used in the Moray Firth trials — see below) are being incorporated into shark nets off South Africa. Dolphins are not deterred from the nets. However, they do appear to have an easier time detecting the nets with reflectors, despite the fact that these nets are made of coarse multifilament line, which should be easy for them to detect. It is expected to take over two years to obtain sample sizes adequate to determine whether the modified nets have lower take rates.[48]

To our knowledge, the first observational study attempting to determine the reactions of small cetaceans to various net-like structures was conducted only recently.[49] The researchers observed the behavior of harbor porpoises (*Phocoena phocoena*) in relation to a 'hukilau' structure.[50] They used a theodolite to track movements of harbor porpoises from shore as they swam near the experimental apparatus. Tests were conducted with only a floatline, and with the floatline strung with verticals of 6.35 mm polypropylene line, 4.76 mm bead chain, and 3.18 mm (inside diameter) surgical tubing. Although sample sizes were small ($n = 13$–38 porpoise approaches for each variable), there were significant differences in responses of porpoises to different materials. Bead chain, and (secondarily) surgical tubing, resulted in greater avoidance of the gear.

Tests similar to those described above[49] have been conducted on bottlenose dolphins in inshore passes around the United Kingdom.[24,51,52] Observers found that dolphins avoided swimming through an experimental apparatus equipped with 67×33.5 mm diameter ellipsoid plastic floats that act as acoustic reflectors. These reflectors increase the target strength of the net, effectively 'in-filling' the space between the headline and the footline.[51] However, they have not conducted similar tests of dolphin reactions to the experimental apparatus without the acoustic reflectors. Without such controls, it is not possible to determine if the reflectors, or some other factor, was responsible for dolphin avoidance of the gear.

2.2. Active methods of reducing fishery interactions

There have been many attempts to deter marine mammals from fishing gear using sound generators (see Tables 1 and 2 for a summary). These methods do not rely on sound production by the animal, and thus have the potential to be effective for deterring mysticetes and pinnipeds (which apparently do not echolocate), as well as odontocetes. Hence, the use of sound generators is one of the most common methods that has been tried for preventing marine mammal–fishery interactions.

By comparing known sound characteristics for particular types of fishing gear, it was found that capture of humpback whales (*Megaptera novaeangliae*) in fishing gear is inversely proportional to the amount of noise made by the net.[53] This finding suggested that adding sound generators to nets may make them easier to detect and avoid. It is important to remember that fish in nets also can significantly modify the acoustic signature of the gear.[53]

2.2.1. *Gunshots*

Probably one of the earliest attempted methods of keeping marine mammals away from fishing activities was to shoot and kill the offending animals. This is effective in some cases for reducing predation on caught fish, but is not useful for the reduction of bycatch, and today is illegal and/or undesirable in many areas.

The act of firing gunshots near a marine mammal, but not hitting it, has also been tried as a method of deterrence. This method probably involves other motivations for avoidance than just the loud sound of the gun, so it is only partially acoustic. Shooting guns to scare seals away from fish farms did not work well with Australian fur seals (*Arctocephalus pusillus doriferus*). Most seals fled when shots were fired, but more than half soon returned.[54]

Gunshots have been used in attempts to keep dolphins away from fishing activities in the Mediterranean. Although there was no scientific monitoring, most attempts appeared to be ineffective.[55] Gunshots also were not an effective means of keeping killer whales away from

TABLE 1

Summary of acoustic studies aimed at reducing cetacean capture in commercial fisheries (includes only studies that were conducted as scientific experiments)

Operation	*Major species*	*Method used*	*Results*[a]	*Sources*
Passive studies				
South African shark gillnet	Bottlenose, humpback dolphins	Foil, aluminum discs, steel wires attached to nets	Inconclusive (low CPUE)	Ref. 45
Northern Australian pelagic driftnet	Bottlenose, spinner dolphins	Bead chain, plastic tubing woven into mesh	Ineffective (insig. DR or increase)	Ref. 44
North Pacific salmon driftnet	Dall's porpoise	Vinyl string, rope, blister sheet woven into mesh	Inconclusive ($n = 13$, no DR calculated)	Ref. 47
		Hollow monofilament sections incorporated into mesh	17% DR^{ns}	Ref. 39
			28% DR**	Ref. 33
			9–20% DR^{ns,**}	Ref. 28
		Multifilament sections incorporated into mesh	9% DR^{ns}	Ref. 33
			28% DR*	Ref. 28
Newfoundland cod trap	Humpback whale	Air-filled pipes, white plastic discs attached to nets	Ineffective	Ref. 68
Active studies				
South African shark gillnet	Bottlenose, humpback dolphins	Clangers, rattles, and bell bouys attached on or near nets	Inconclusive (operational problems)	Ref. 45
Newfoundland cod trap	Humpback whale	Low freq. clangers	0% DR^{nt}	Ref. 107
		High freq. pingers	Increase	Ref. 107
		Low freq. beepers	42% DR^{nt}	Ref. 107
		Louder low freq. alarms	66% DR^{nt}	Ref. 108

Newfoundland gillnet	Humpback whale	Alarms (similar to low freq. beepers above)	Inconclusive (low CPUE)	Ref. 68
		Fishing salutes thrown into water	Ineffective (no scientific monitoring)	Ref. 68
North Pacific salmon driftnet	Dall's porpoise	Whistle sound generator (SG1)	3–10% $DR^{ns,*}$	Ref. 28
		145 kHz generator (SG2)	5–13% DR^{ns}	Ref. 28
		135–150 kHz variable generator (SG3)	7–16% $DR^{ns,*}$	Ref. 28
		20–50 kHz 'alarm' generator (SG4)	19% DR^{ns}	Ref. 28
Gulf of Maine groundfish gillnet	Harbor porpoise	Low frequency acoustic alarms	Promising (preliminary)	Ref. 115
Combinations				
North Pacific salmon driftnet	Dall's porpoise	Sound generators attached and hollow mono-	10% DR^{nt}	Ref. 33
		filament incorp. into mesh	19–39% DR^{ns}	Ref. 28

[a] DR refers to decrease rate (percent reduction in take rate of experimental gear versus unmodified gear).
Significance levels: *0.05, **0.01, ***0.001, [ns] not significant, [nt] not tested.

TABLE 2
Summary of acoustic studies aimed at deterring pinnipeds from fishing operations (includes only studies that were conducted as scientific experiments, or were reported in the technical literature)

Operation	*Species*	*Method used*	*Results*[a]	*Sources*
Various Washington salmon gillnet fisheries	Harbor seal	Seal bombs	Increase to 16% DR^{ns} in percent of catch damaged	Ref. 96
		AHD	62% DR* and 68% DR* in fish damage	Ref. 96
		Cracker shells	Increase in fish damage	Ref. 96
Columbia River gillnet fishery	Harbor seal	AHD	94% DR^{nt} in percentage of catch damaged	Ref. 93
Yaquina Bay	Harbor seal	AHD	No data — effective for excluding most animals	Ref. 98
Netarts Bay salmon hatchery	Harbor seal	AHD	81% DR^{nt} in number of seals observed	Ref. 93
Coos Bay salmon recapture facility	California sea lions and harbor seal	Cracker shells, bottle rockets, and AHD	No data — mixed results	Ref. 80
Klamath River gillnet fishery	Harbor seal	AHD	Most seals successfully herded	Ref. 61
Klamath River salmon seining operations	Harbor seal	AHD	Mixed success	Ref. 97
San Francisco Bay herring gillnet and purse seine fisheries	California sea lion	AHD and cracker shells	Successful deterrence with 2 methods combined	Ref. 103

Southern California party-boat fishery	California sea lion	Cracker shells	5.0–7.5 min. MTA	Refs. 97, 103
		AHD	4.0 min. MTA	Ref. 97
		Cracker shells and AHD	6.0 min. MTA	Refs. 65, 97
	Harbor seal	Cracker shells and AHD	14 min. MTA	Ref. 97
Southern African trawl and purse seine fisheries	South African fur seal	'Beluga', Thunderflash fire-crackers, seal bombs	70% fled, most returned	Ref. 62
		Killer whale calls	All dove, none fled	Ref. 62
		Gunshots	Repeated shooting caused most seals to flee	Ref. 62
		Arc discharger	Signif. DR in number of seals during trawling, but not purse seining	Ref. 62
Tasmanian fish pens	Australian fur seal	Gunshots	95% fled, but 51% returned	Ref. 54
		Boat harassment	100% fled, 27% returned	Ref. 54
		AHD	0% fled	Ref. 54
Chittenden Locks fish ladder	California sea lion	Seal bombs and AHD	97% DR in predation rate (but decreased in later seasons)	Ref. 63

[a] DR refers to decrease rate. MTA refers to median time away (median of the time that a particular device kept pinnipeds away). Significance levels: * 0.05, ** 0.01, *** 0.001, [ns] not significant, [nt] not tested.

longlines in Alaskan waters.[56,57] Fishermen reported that killer whales have been shot and killed in the Bering Sea, and that other killer whales have left the area when one of their pod was shot.[58] None of the attempts to use gunshots as deterrents has been done as part of a controlled experiment, so we only have subjective impressions on their effectiveness.

2.2.2. *Explosives*

Explosives have been used extensively in attempts to scare pinnipeds away from fishing activities. One type of explosive, the 'seal bomb' was developed and manufactured commercially for such purposes. Seal bombs are large firecrackers (like M80s and cherry bombs) weighted with sand to sink and explode underwater, creating a loud sound and a flash of light. Most of the energy released is below 1 kHz, and the source level[59] is about 190 dB re 1 microPascal.[60] These explosives pose a danger of accidental injury to the person igniting them.

Seal bombs were used to herd harbor seals (*Phoca vitulina*), but the researchers found some learned avoidance and the animals became habituated to the explosives.[61] Various underwater explosives (Thunderflash and Beluga firecrackers, and seal bombs) were used to deter South African fur seals (*Arctocephalus pusillus pusillus*) from nets off South Africa.[62] None of the explosives used in this situation was found to be very effective; most seals that left the area soon returned. Seal bombs were largely ineffective in scaring Australian fur seals from fish pens in Tasmania, but no specifics were provided.[54] The use of seal bombs and other acoustic methods, although showing some initial effectiveness, became less useful over time in attempts to deter California sea lions from preying on steelhead trout at Chittenden Locks in Seattle, Washington.[63]

Cracker shells have been used in attempts to keep harbor seals and California sea lions (*Zalophus californianus*) away from both commercial and sport fishing activities off the west coast of the United States. Cracker shells are charges fired from a rifle or pistol, which then explode in the air or underwater near the surface. They generally produce less underwater energy than seal bombs do, and source levels are quite variable, depending on how close to the surface they explode (170–235 dB re 1 microPascal).[60] For pinnipeds, the charges probably need to explode very close-by to be effective as deterrents.[60] In southern California, cracker shells were not effective, keeping sea lions away from fishing areas for only about 5 minutes.[64] However, they showed some success with harbor seals, when used in conjunction with an acoustic harassment device (nearly tripling the time the seals stayed away).[64–67]

Fishing salutes are essentially the same as seal bombs, and they have not been successful in reducing large whale collisions with gillnets in Newfoundland. However, no systematic data have been collected, and the researchers have had to rely on interviews with fishermen.[68] Seal bombs were found by fishermen to be ineffective for deterring killer whales from longline gear in Alaskan waters.[57,58,69–71] Blasting caps also have been tried in the latter situation, mostly unsuccessfully; only much larger explosives have had positive deterrent effects on Prince William Sound killer whales.[67–71] Even dynamite was not effective in keeping killer whales away from longline gear in the Bering Sea.[58] Such large explosives are very dangerous, both for the whales and for the fishermen. Large industrial explosions, of about 5000 kg, have been shown to cause damage to the ears of humpback whales,[72] and may kill marine mammals in the area.

Since at least 1980, seal bombs have been used in the tuna purse seine fishery in the ETP to herd dolphins during sets.[73,74] There has been much controversy over the use of these devices, and they have been banned by the United States. Although there is an absence of evidence for increased dolphin mortality during sets in which the bombs have been used,[73] they can cause injury, such as shattered skeletal bones, when exploded less than 4 m away from the animals.[75,76] Homemade 'pipebombs' of the type also used in the ETP can cause serious injury or death when detonated at less than 0.5 m from dolphins.[77]

Shrimp trawlers off West Africa have attempted to scare bottlenose dolphins from their nets by using explosives.[78] Explosives used to deter dolphins in the Mediterranean were reported to be largely unsuccessful.[55] However, few details were given in descriptions of the above attempts. Underwater firecrackers reportedly had no effect on Dall's porpoises in the North Pacific.[26] Surprisingly, 'water bombs' with a source level of 213 dB re 1 microPascal also did not detectably affect the behavior of captive false killer whales (*Pseudorca crassidens*).[79] Bottle rockets also have been tried, but there are few data available on their effectiveness.[80,81]

2.2.3. *Biological sounds*

Since initial work showing avoidance responses of gray (*Eschrichtius robustus*) and white (*Delphinapterus leucas*) whales to killer whale vocalizations, the sounds of this natural predator have been investigated in several cases as a method of deterring marine mammals from fishing gear.[82,83] The above studies were both short-term and the potential for habituation to the stimulus, if used over longer periods of time, should be considered. The potential for habituation in the white whale study was considered to be insignificant.[83] This is because of the short time period (two weeks each year) that the deterrents needed to be in place to effectively protect salmon runs in the stretch of river in which they worked, and the likelihood that white whales are exposed routinely to real killer whales.

Pinnipeds sometimes have shown immediate avoidance responses to projection of killer whale sound recordings, but generally habituate quickly.[62,84] Dall's porpoises, on two occasions, disappeared when exposed to projection of killer whale sounds in the North Pacific.[26] Playing of killer whale sounds to dolphins in tuna purse seines had no obvious useful effect in herding the animals in the net.[20]

In most instances, killer whale sounds have been found to be ineffective in deterring marine mammals. This is not surprising, in view of the fact that often there was no attempt made to use sounds that would be specific to hunting transient killer whales. Interactions between killer whales and other marine mammals are complex, probably involving multiple sensory cues.[85] Potential marine mammal prey (especially in areas where they come into frequent contact with killer whales) probably have sophisticated abilities to assess the danger posed by killer whales making certain types of sounds. They also probably use not only hearing, but also other sensory means to assess the danger when they encounter killer whales.[85] So, even if the animals initially are 'fooled' by the projection of killer whale sounds, we suggest that they eventually may learn that it is a 'hollow threat', and begin to ignore the stimulus (it should be noted that this may make them more vulnerable to predation by real killer whales).

Recorded dolphin sounds have been played to dolphins in tuna nets in an attempt to aid in releasing them, unharmed, from the nets. However, these attempts have not been effective in attracting or herding the animals toward the backdown area.[19,20,86] The use of dolphin sounds ('distress calls', etc.) played underwater to deter dolphin predation on fishing activities in the Mediterranean Sea and along the Atlantic coast of Morocco has been suggested, but we know of no studies that quantify their effectiveness.[55] In fact, the idea of a specific call or sound associated with distress in cetaceans is not well-supported, and may be an outdated concept.

2.2.4. *Mechanical sound generators*

Non-electronic clangers, rattles, and bell bouys have been used to try to reduce entanglement of bottlenose and humpback dolphins in shark nets off South Africa.[45] The nets equipped with sound generators still caught dolphins, but the low overall catch rate and logistical problems caused termination of the project before statistically meaningful results could be obtained.

'Bang pipes' have been used in attempts to scare dolphins away from yellowtail fishing grounds off Japan.[87,88] Bang pipes are steel tubes that are lowered into the water and hammered, to create a 'banging' noise. Although bang pipes are used elsewhere in Japanese dolphin drives to herd dolphins toward shore, they have been mostly unsuccessful in deterring dolphins from fishing grounds, especially after several periods of use (probably due to habituation).

Bang pipes were not effective in deterring killer whales from the vicinity of longlines in Alaska.[57,71] Bang pipes, on some occasions, caused an avoidance response in captive false killer whales, but the short-term nature of the experiment did not permit an evaluation of habituation to the sounds.[79] Among many other methods, bang pipes were used with some success to harass the humpback whale 'Humphrey',[89] in an attempt to rescue him from the Sacramento River in northern California.[90]

2.2.5. *Electronic sound generators*

Various electronic devices that produce sound have been used in attempts to deter marine mammals. Pure and pulsed tones (electronically generated), and various loud noises (tape recorded) were played to a captive harbor seal, and no consistent avoidance responses were found.[84] Sound generators have been used in an attempt to keep gray (*Halichoerus grypus*) and harbor seals from fish farms in Scotland, but we know of no data on their effectiveness.[91]

The responses of two captive false killer whales to various electronically generated pulses varying from 0.2 to 200 kHz, with source levels from 181 to 219 dB re 1 microPascal were tested.[79] Most pulse types tested were ineffective or only slightly effective, and those that did elicit a response became less efficient with repetition.

An experiment with a radio-controlled boat (powered by a chainsaw engine, making a loud noise) was conducted in an attempt to reduce predation of California sea lions on steelhead trout at Chittenden Locks in Seattle.[63] Although the sea lions showed some reaction to the boat, they did not leave the area. Other methods have been proposed to solve this problem, but we are unaware of reports on their effectiveness.

Acoustic Harassment Devices (AHDs) were developed in the early 1980s to keep harbor seals along the United States west coast away from fishing activities.[92] The devices produce an irregular, pulsed, broad-band sound within the hearing sensitivity of the harbor seal (12–17 kHz). The sound is loud (source levels are about 175–210 dB re 1 microPascal)[60] and is intended to be unpleasant to the animal, to keep it from entering the area of use or to cause it to flee if already there. Acoustic Harassment Devices are generally preferable to seal bombs and cracker shells (which were already in use in several areas when AHDs were introduced), because they are safer for the fishermen, and are less labor-intensive, since they operate automatically.

The system showed some early success in reducing predation rates of harbor seals on gillnet-caught and hatchery fish, but some seals appeared to be unaffected by the AHD.[93] The system was designed to be irritating, but not necessarily painful, to pinnipeds.[60,94] However, if the motivation for remaining in the area is strong, simple discomfort may not be enough to deter the animal. The seals can habituate to the sounds produced by the devices, and may simply avoid being exposed to the stimulus by holding their heads out the water during the intermittent periods when the devices are projecting sounds. It should also be noted that various environmental conditions and the location and orientation of the animal in relation to the AHD can affect the sound perceived by the animal.[60,95]

This original type of AHD system has been used extensively in attempts to deter pinnipeds in several locations on the west coast of the United States, with little long-term success.[63,80,96–98] In general, the system has only been moderately effective for most harbor seals, although some individuals (possibly deaf or hearing-impaired animals) appeared totally unaffected by it, and some degree of habituation has almost always been found. Some seals have learned to avoid the sounds by sticking their heads out of the water, or by using sound shadows caused by solid barriers.[80] It has been argued that habituation can be avoided or delayed by mixing different stimuli, or introducing the illusion of a moving stimulus.[99]

The AHD system does not work well for deterring sea lions.[63,80,99] This is probably because it was designed to be maximally disturbing to harbor seals, and sea lions have different hearing characteristics, with a higher pain threshold.[93,100] The pain threshold for harbor seals has been estimated as 120 dB re 1 microPascal above the audibility threshold, or about +185 dB re 1 microPascal.[100] For sea lions, the threshold is estimated to be +200 dB re 1 microPascal, and the original AHDs did not achieve a sound pressure this high.[100] A fisherman in an experimental salmon troll fishery in California used an AHD with apparent initial success in keeping sea lions away. But after a few days, he observed some predation, and finally stopped using the device when it appeared to act as a 'dinner bell'[101] for the sea lions.[102] In the Sacramento River, an AHD was useful in keeping away a sea lion preying on fish that were caught with gillnets. However, this deterrent was not effective in reducing predation, since the sea lion simply took fish from parts of the net farther away from the device.[102]

Acoustic harassment devices, when coupled with the use of other methods, such as cracker shells or seal bombs, have been found to be somewhat effective in deterring sea lions. They increased the median time that sea lions stayed away (MTA) from a sportfishing area in southern California, from 4 to 6 minutes.[65,103] However, even in one situation (Chittenden Locks, Seattle), in which this combination was nearly 100% effective in the first season of use, it became less effective in later seasons, due to habituation.[63]

A Swedish company (Kemers Maskin AB) has recently developed a high-power AHD system. It is being marketed by a fisherman in Monterey, California, but we know of no tests of its effectiveness.

An arc discharger (similar to an AHD) caused South African fur seals off southern Africa to flee from trawls, but not from purse seines.[62] Automatic seal-scaring devices (transmitting frequencies of 10 and 28 kHz) were not useful for deterring Australian fur seals from fish pens in Tasmania; there was no avoidance in any of the 60 attacks in which the devices were used.[54] Similarly, acoustic deterrents (presumably AHDs) have shown 'poor results' in keeping South American sea lions (*Otaria byronia*) away from fish farms in southern Chile, although no details were given.[104] Acoustic devices are known to be used also in British Columbia, Canada, to deter pinnipeds from fish farming operations, but we have found no descriptions of their effectiveness.

Acoustic harassment devices have been used to try to scare dolphins from fishing areas around Iki Island, Japan, without much success.[105] An AHD system appeared to cause killer whales to leave longline fishing areas in Alaska, but the animals soon returned.[71] Acoustic harassment devices with source levels lower than approximately 190 dB re 1 microPascal did not work to keep killer whales away from longline vessels in Prince William Sound.[58]

Numerous studies have been conducted on the use of net alarms in attempts to reduce marine mammal entanglement in fishing gear. The assumption here is that the animals are unaware of the net, and that a sound emitter attached to the net will indicate its location to the animal. If the animal will then avoid the net, knowledge of the net's location may reduce the possibility of accidental collision. Although small cetaceans probably, in most cases, do not survive net collisions, large whales often escape from fishing gear, enabling them to learn of the danger nets pose. Acoustic alarms thus may make it easier for whales to exhibit natural or learned avoidance responses when they encounter fishing nets.

Initial positive results using sound generators (alarms) to reduce the occurrence of large whale collisions with fishing gear in Newfoundland[106] have been confirmed by later studies. Unfortunately, studies in Newfoundland have relied on interviews with fishermen to assess their effectiveness, and there are no independent observer data. Several types of sound emitters were used on Newfoundland cod traps, and the researchers concluded that low frequency (3.5 kHz) 'beepers' reduced, to nearly half, the frequency of captures of large whales.[107] However, the effectiveness of alarms in reducing collisions with gillnets could not be statistically determined, due to the infrequency of collisions with this type of gear.[68] Later tests with louder, low frequency whale alarms on cod traps greatly reduced the collision rate (0.02 collisions/net versus 0.35 without alarms, statistical significance not reported).[108] In observational experiments, humpback and minke (*Balaenoptera acutorostrata*) whales approached traps several times, but did not contact those with activated acoustic alarm devices, and collided with traps that had non-operating alarms.[109,110] This suggests that the whales are aware of the location of the operating devices, and that this helps them avoid collisions with nets actively using them.

Sound generators (SGs) have usually not been effective in reducing bycatch of small cetaceans, despite speculation that such methods of warning Dall's porpoises likely would reduce take rates in Japanese driftnets.[9,40] In one study, responses of captive bottlenose and pantropical spotted dolphins to prototype whale alarms were tested. Dolphins approached both operating and non-operating alarms, but habituated to them over time and soon began ignoring them.[111]

Japanese salmon driftnets equipped with sound generators were reported to have lower catch rates of Dall's porpoises.[33–38,112] Four types of sounds were used. The first (SG1) was based on the structure of bottlenose dolphin whistles, the second (SG2) emitted constant-period 145 kHz pulses, the third (SG3) produced random-period 135–150 kHz pulses, and the final one (SG4) was a 20–50 kHz 'alarm' call simulator. Reductions of 3–19% in take rate for sound generator nets versus standard nets were reported. The highest decrease rate was with SG4, but the sample size was small ($n = 13$ sets), and results were not statistically significant.[23,28]

There is a possibility that the data from the Japanese salmon driftnet fleet were seriously biased. The Japanese fishing fleet commanders were responsible for determining where all the catcherboats would set their nets, including those with modified gear. The placement of nets with modified gear was thus not necessarily random, and may have occurred preferentially in areas with low porpoise density.[113]

Sample sizes for US observer data on sound generator effectiveness in this fishery were considered to be too small for statistical analysis ($n = 51$ and 73 for two types of generators).[39] The lower frequency (9 kHz) devices, however, actually had a higher take rate than did the standard nets.

Sound emitters have reportedly been 'used with fairly good effect' to keep dolphins away from fishing boats off Spain.[55] Acoustic pingers and underwater projection of white noise to dolphins in ETP tuna purse seines were not effective in herding or corraling them.[20]

Recently, work has been conducted using the type of net alarms described above,[108] to try to reduce entanglement of harbor porpoises in gillnets in the Gulf of Maine. Alarms were clipped onto the headrope of the net. Experimental studies with harbor porpoises in captivity showed that acoustic alarms can have dramatic effects on porpoise behavior, but that the effects can be quite variable, depending on the signal and alarm characteristics.[114] Preliminary results of harbor porpoise catch rates in nets with acoustic alarms appeared to be promising,[115] but an evaluation of their effectiveness will depend upon rigorous scientific testing with large sample sizes (a larger-scale study is in progress). In particular, the possibility of habituation needs to be assessed over time, and methods of reducing the probability of habituation should be pursued.[114]

2.3. Other methods of reducing fishery interactions

Vessel chases and boat noise have been found to be effective in herding marine mammals in some cases. Boats have been used to scare seals away from fish farms in Tasmania.[54] In the ETP, tuna fishermen use the wake of the vessel and speedboats (some equipped with chains that rattle against the steel hull) to herd dolphins. Apparently, both the sound of the bubbles in the wake and the reflection of sonar clicks by the wake are important.[17] The use of radio-controlled model boats, which produce a loud noise, did not cause sea lions to leave locks where they were preying on trout.[63]

Recent work on killer whale–longline interactions in Alaska has focused on making fishing operations less noisy, and thus less detectable to killer whales from a distance.[116] This would be done by noise masking (using fire hoses and bubble screens) and acoustically decoupling the vessel's engine from the hull (with rubber pads between the engine mount and the hull). The effectiveness of these methods has not yet been assessed.

3. CONCLUSIONS

Most previous attempts to deter marine mammals from fishing activities have been based upon trial and error, with few controlled experiments (see Tables 1 and 2). Often, the fishermen, understandably unwilling to wait for the slow process of science to provide a solution, have 'taken matters into their own hands', experimenting on their own with various techniques. In some cases we have had to rely on their subjective impressions of the effectiveness of various methods of deterring marine mammals. Where scientific testing has taken place, it rarely has been conducted in a manner that produced unbiased, reliable results (this generally requires large, statistically-valid samples; proper controls; and data collected by independent observers). It is even rarer for these studies to be published in the primary scientific literature, where they can receive peer review, and add to a foundation of knowledge that can be built upon by later studies. As a result, it is very difficult to draw solid conclusions from the extensive body of work that has been done in this area. The paucity of information on the reasons for marine mammal bycatch in many fishing situations appears to have, so far, led to little success in using sound to resolve marine mammal–fishery conflicts. Work aimed at reducing interactions of marine mammals with fisheries activities has moved on to non-acoustic approaches in many cases; for instance, the use of visual deterrents and taste aversion on pinnipeds in California and Tasmania.[81,117,118]

It is clear that several changes in research priorities and management practices will be needed before any substantial improvement in the likelihood of success of acoustic studies can be expected. Field tests and studies of echolocation rates and capabilities should be conducted on a variety of marine mammal species in different areas. The effects of environmental factors should be evaluated. More must be learned of how, and how often, cetaceans use their sonar in their natural environment. We are woefully ignorant in this area. Although this type of work is logistically difficult, it is badly needed.

Scientists and gear technologists should work with fishermen in designing potential fishing modifications. Tuna fishermen were instrumental in the design and testing of many of the modifications to gear and practice that resulted in great reductions in the number of dolphins killed per year in the ETP fishery. Fishermen may have suggestions for modifications that should be considered in attempts to reduce cetacean entanglement, and they are able to consider the real-life implications of a potential modification on the fishing process much better than others. Fishing community leaders must be made into allies, not enemies. By gaining the support of such influential leaders, fishermen can be convinced more easily of the need for cooperation to solve cetacean–gillnet interaction problems.

Studies of acoustic deterrents must be well-designed and planned to provide statistically valid assessments of whether the deterrents are effective. However, it should be kept in mind that, in many cases, the magnitude of the required reductions will be so large that simple statistical tests showing small, but significant, results will not be adequate. They must be run with enough repetitions to take into account the possibility of habituation. Experimental and control trials should ideally differ only in presence or absence of the experimental stimulus. Decrease rates (based on independent observer data) should be computed for each type of experimental gear, to allow comparison with other studies. These studies should include (where possible) behavioral observations of animals around the experimental gear to determine the mechanisms of entanglement and the reasons for any reduction in take rate. Finally, the results should be published in a timely manner in the primary scientific literature. We feel that no further funding should be given to proposed deterrent studies that do not satisfy the conditions above.

While work addressing acoustic modifications to gillnets and other types of fishing gear should continue in cases where there is not a threat to marine mammal populations, until workable solutions are found, other methods of reducing bycatch should be used. It is likely that gillnet modifications may never provide workable solutions in many cases. Managers and fishermen should acknowledge this and that, in some cases, time and area closures or switches to more selective gear types will be required to prevent the depletion of stocks of marine mammals and other slowly-reproducing vertebrates.

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